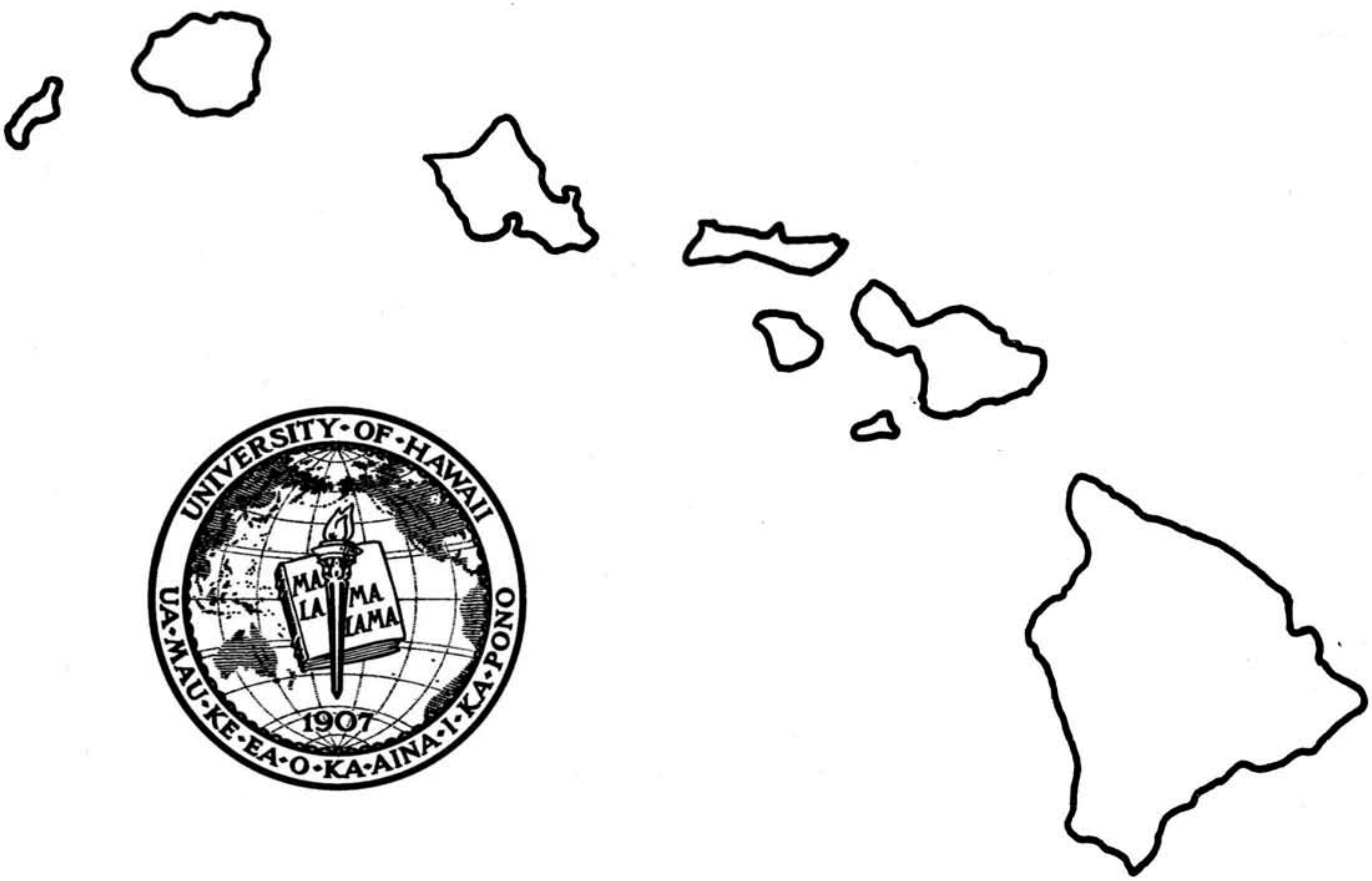
# THE HAWAII GEOTHERMAL PROJECT

QUARTERLY PROGRESS REPORT NO. 4

March 1, 1974 Through June 30, 1974



# THE HAWAII GEOTHERMAL PROJECT

## QUARTERLY PROGRESS REPORT NO. 4

March 1, 1974 Through June 30, 1974


SUPPORT FOR PROJECT PROVIDED BY:

National Science Foundation
State of Hawaii
County of Hawaii



| | |
|---|---|
| Management Program | John W. Shupe |
| Geophysical Program | Augustine S. Furumoto |
| Engineering Program | Paul C. Yuen |
| Socioeconomic Program | Robert M. Kamins |
| Drilling Program | Agatin T. Abbott |

University of Hawaii
Holmes Hall 240 - 2540 Dole Street
Honolulu, Hawaii 96822



HGP-QPR 4

HAWAII GEOTHERMAL PROJECT

FOURTH QUARTERLY PROGRESS REPORT

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# HAWAII GEOTHERMAL PROJECT

## QUARTERLY PROGRESS REPORT IV
March 1 Through May 31, 1974

### INTRODUCTION

The fourth quarter was a most productive period for the Hawaii Geothermal Project: (1) all three research programs continued to make good progress with planned research activity; (2) State legislative interest in geothermal energy was evidenced by passage of House Bill 2197-74, to establish legal and regulatory guidelines for geothermal development, and by appropriation of $500,000 in the Capital Improvements Project Budget for exploratory geothermal drilling; and (3) the second increment of funding was received from the National Science Foundation as operational support for the HGP through the remainder of calendar year 1974 -- $216,600 from the FY 74 Budget and, "contingent on the availability of FY 75 funds, it is the Foundation's intention to provide an additional $118,700 for support of this project."

A disproportionate amount of effort during this quarter was devoted to proposal preparation: first, the 107-page proposal to NSF for continuing operational support through December 31, 1974, which resulted in the $335,300 commitment listed above; and, more recently, a 324-page proposal to NSF for $1,986,513 to run from January 1 through December 31, 1975, and which would permit the initiation of an exploratory research drilling program, as well as continue support for the Geophysical, Engineering, and Environmental-Socioeconomic Programs. Since this is a multimillion dollar proposal, at least six months lead time is required by NSF for proposal review prior to the January 1 starting date.

Because of the extensive amount of time spent by the five principal investigators and their supporting staffs in proposal preparation, efforts were made to lift as much of the information as possible directly from this most recent proposal to provide the basis for the Fourth Quarterly Progress Report. Consequently, the narrative which follows, in addition to presenting a summary of the progress of Phase I of the HGP up to this point, also provides an outline of the goals to be realized through the remainder of Phase I and the initiation of Phase II -- the exploratory drilling program. This discussion is presented under the following general headings:

Overview of Phase I and II
Management Program
Geophysical Program
Engineering Program
Environmental-Socioeconomic Program
Drilling Program

A rough time schedule of HGP activity in the months ahead includes a maximum research effort by all research programs and field survey teams during the summer, with the fall devoted to data interpretation and analyses. A joint meeting of the National Liaison Board and the Hawaii Advisory Committee is tentatively set for November 1974, at which time HGP personnel will present findings to date. This should generate feedback and discussion, which will provide input to Dr. Abbott and his site selection committee to assist in finalizing plans for the exploratory drilling program to begin in early 1975.

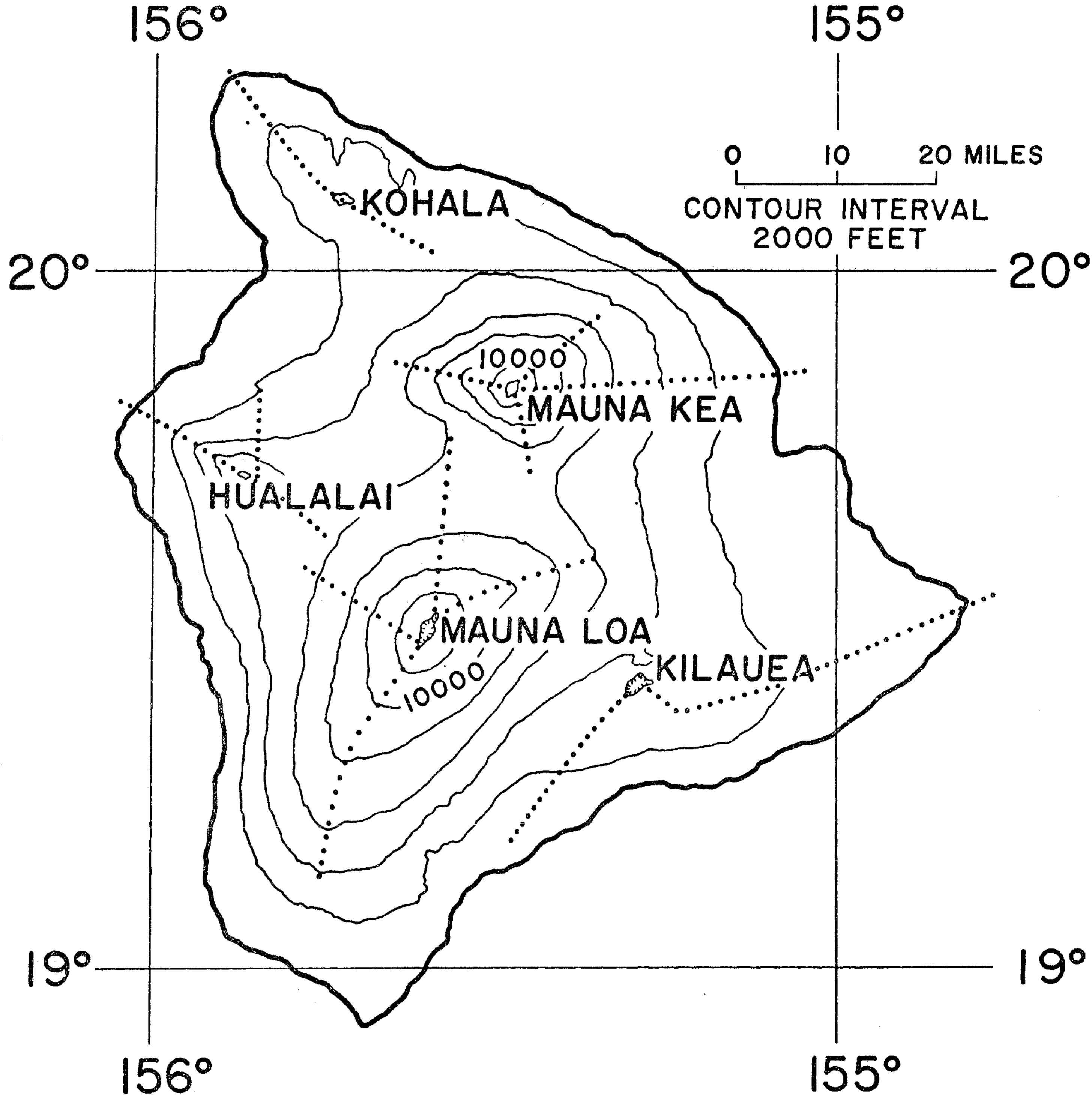
Since the remainder of 1974 will be utilized by all research directors to concentrate on completing the research tasks for Phase I, no additional quarterly progress reports will be prepared, other than an administrative summary by the Project Director. It is the consensus of the Executive Committee that time can be spent more productively on the research effort, and that a comprehensive report will be prepared for distribution at the completion of Phase I on December 31, 1974.

## OVERVIEW OF PHASES I AND II OF THE HGP

The Hawaii Geothermal Project (HGP) was organized to focus the resources of the University, the State, and the County of Hawaii on the identification, generation, and utilization of geothermal energy on the Big Island of Hawaii. Figure 1 shows the five volcanoes which form this largest island in the Hawaiian chain. Hawaii is also the youngest of the islands and is still experiencing growth from recent activity of the Mauna Loa and Kilauea volcanoes. Consequently, the Big Island was selected as the obvious site for initial geothermal exploration, but subsequent surveys will proceed up the island chain.

The research program as developed by the HGP involves an interdisciplinary team of researchers from throughout the University system, which conduct scientific investigations on both short-range exploratory and applied technology tasks to assist in the early development of any conventional geothermal resource -- steam or hot water -- that may exist on the Big Island, as well as long-range research studies of a more basic nature. The overall goals and objectives of the HGP, many of which will contribute to the technology base for the recovery of energy from subsurface heat, no matter where it occurs, include:

1. Improvement of geophysical survey techniques for locating underground heat resources.
2. Identification of potential geothermal resources, initially on the Big Island, but ultimately for the entire island chain.
3. Experimentation with deep-drilling techniques for subsurface heat.
4. Development of efficient, environmentally clean systems for conversion of underground heat resources to useful energy.




VOLCANOES & RIFT ZONES ON THE ISLAND OF HAWAII

Figure I

5. Completion of socioeconomic and legal studies for conversion of underground heat resources to useful energy.

6. Establishment of environmental base lines with which to monitor subsequent geothermal development.

7. Development of a geothermal production field and prototype power plant on the Big Island, which will serve as a National Geothermal Energy Laboratory on technological developments in power production and reservoir management of earth heat resources.

The HGP came into being when the 1972 Hawaii State Legislature allocated $200,000 for geothermal research -- $100,000 to be administered through the County of Hawaii budget. This action was taken prior to the energy crisis and was a progressive step for a state governing body to take. An initial grant of $252,000 was received from the Research Applied to National Needs Program of the National Science Foundation in May 1973; the State and County of Hawaii released their $200,000 shortly afterwards; and Phase I of the HGP got underway during the summer of 1973.

Research for Phase I was organized into three separate programs, with the initial $452,000 budget supporting the following activity:

<u>Geophysical Program -- Augustine S. Furumoto, Director</u>

Photogeologic (Infrared Scanning) Survey
Electromagnetic Survey
Electrical Resistivity Survey
Microearthquake and Microseismic Surveys

<u>Engineering Program -- Paul C. Yuen, Director</u>

Well Test Analysis
Ghyben-Herzberg Lens Dynamics
Energy Extraction from Hot Brine

<u>Environmental-Socioeconomic Program -- Robert M. Kamins, Director</u>

Land Use, Regulations and Planning
Economic Analysis

The major emphasis of Phase I has been on the Geophysical Program, since the issue of if and where geothermal resources exist is crucial to the Project. However, parallel engineering studies were initiated to investigate problems involving reservoir characteristics and plant design, and legal studies were begun to help clarify regulatory and ownership rights -- since these points must be resolved before any investment capital can be identified for geothermal development in Hawaii. Good progress has been made to date in all three programs and is summarized in subsequent sections of this proposal.

It was impossible to complete the geophysical surveys and to analyze all of the data associated with the field studies during the first year of the Project. Therefore, a proposal for a continuation grant of $340,000 was made to the National Science Foundation to provide operating support for the Phase I research program through calendar year 1974. This proposal was funded by the Foundation, and currently the HGP is fully mobilized to complete this phase of the study. The geophysical surveys to date have been primarily reconnaissance surveys to identify general areas of potential interest. The remainder of 1974 will be devoted to refining the preliminary geophysical results and, to assist in this endeavor, a new task on Geochemical Surveys has been added. Parallel studies will continue in the Engineering and Socioeconomic Programs, with preliminary work beginning on establishing environmental baselines to assist in monitoring subsequent drilling operations.

On the basis of preliminary results from Phase I, in conjunction with surveys and studies conducted on the Big Island by a variety of scientific disciplines over the past several decades, it has become obvious that an exploratory research drilling program is essential to establish actual identity of the subsurface conditions predicted by the surveys. The major thrust of this proposal is to initiate the drilling program as Phase II of the HGP, in order to verify interpretation of the scientific data and to determine if conventional geothermal resources exist on Hawaii. Research activity will also continue in each of the three complementary programs: Geophysical, Engineering, Environmental-Socioeconomic.

Referring again to Figure 1, tentative plans call for initial drilling to take place in early 1975 along the Eastern Rift of Kilauea, followed by the Southwest Rifts of Kilauea and Mauna Loa. At each location the drilling program will include a number of shallow holes a few hundred feet deep, a smaller number of holes 2,000 feet or so in depth, and one deep hole that may extend to 6,000 feet. The drilling program will be under the direction of Dr. Agatin T. Abbott and the Site Selection and Operations Committee, which he established to assist with key decisions both for preliminary planning and as drilling progresses. Tentative scheduling, operation, and information to be obtained from the drilling program is discussed in detail in a subsequent section.

In summary, the overall objective of Phases I and II of the HGP is to solve the problems and to answer the questions -- geophysical, technological, legal, environmental, social, economic -- relating to the development of a conventional geothermal resource in Hawaii. If such a resource is identified, it is the intent to carry this development to the proof of concept stage, through the construction of a 5- to 10-megawatt prototype geothermal power plant. This will be done in cooperation with the local electrical utility, which is expected to finance the basic cost of the plant and include it in the electric system for the Big Island. The HGP will endeavor to identify public funding in order to: (1) make the entire operation environmentally pure, as a demonstration of the non-polluting potential of geothermal energy; and (2) instrument both the wells and the plant sufficiently so that adequate operational data and reservoir characteristics can be obtained. This instrumented prototype power plant and geothermal field will form the nucleus for a National Geothermal Energy Laboratory to be used by engineers and scientists from throughout the world to study reservoir characteristics and evaluate performance theories.

BUDGET SUMMARIES

Direct support to the Hawaii Geothermal Project through December 31, 1974 is as follows:

| | | |
|---|---|---|
| National Science Foundation - RANN | $252,000 | (FY 73) |
| | 216,600 | (FY 74) |
| | 118,700 | (FY 75 committed) |
| State of Hawaii CIP Budget | 100,000 | (FY 72) |
| | 500,000 | (FY 74 appropriated) |
| County of Hawaii CIP Budget | 100,000 | (FY 72) |
| Sandia Laboratories - AEC | 12,000 | |
| Hawaiian Electric Company | 9,000 | |
| Office of Marine Affairs - State of Hawaii | 5,000 | |
| Private Contributions | 13,000 | |
| | $1,326,300 | |

In addition to the above funding, the University of Hawaii provides significant support to the Project in faculty and staff salaries, support services, equipment, and facility usage.

For support of Phase II of the Project, $1,986,513 is requested. Table B-I gives a summary of the funding being requested from the Foundation for Phase II of the Project, broken down by program and task.

# HAWAII GEOTHERMAL PROJECT

## PHASE II

## BUDGET SUMMARY BY PROGRAM AND TASK
January 1 Through December 31, 1975

| | | | |
|---|---|---|---|
| MANAGEMENT | | | |
| 1.0 | Coordination and Support | | $ 39,401 |
| GEOPHYSICAL PROGRAM | | | |
| 2.0 | Coordination and Support | $ 43,454 | |
| 2.2 | Geoelectric Surveys | 58,709 | |
| 2.3 | Modelling, Magnetic & Gravity Surveys | 33,625 | |
| 2.4 | Temperature Survey | 43,124 | |
| 2.5 | Seismic Studies | 57,000 | |
| 2.6 | Geochemical Surveys | 36,718 | |
| 2.7 | Hydrology | 35,107 | |
| 2.8 | Physical Properties of Rocks | 49,191 | |
| | | | 356,928 |
| ENGINEERING PROGRAM | | | |
| 3.0 | Coordination and Support | 41,774 | |
| 3.1 | Geothermal Reservoir Engineering | 122,892 | |
| 3.6 | Optional Geothermal Plant Design | 87,781 | |
| | | | 252,447 |
| ENVIRONMENTAL-SOCIOECONOMIC PROGRAM | | | |
| 4.0 | Coordination and Support | 24,824 | |
| 4.1 | Environmental Aspects | 42,313 | |
| 4.2 | Legal and Regulatory Aspects | 6,800 | |
| 4.3 | Land-Use and Planning Aspects | 11,415 | |
| 4.4 | Economics | 46,411 | |
| | | | 131,763 |
| EXPLORATORY RESEARCH DRILLING PROGRAM | | | |
| 5.0 | Coordination and Support | | 1,205,974 |
| | TOTAL PHASE II BUDGET | | $1,986,513 |

TABLE B-I

## MANAGEMENT PROGRAM (1.0)

### A. The Management Plan

The Hawaii Geothermal Project involves more than forty researchers and support staff from throughout the University of Hawaii system. Both major campuses on Oahu and the Big Island are represented, along with over a dozen research institutes and academic units. Many of the State and County agencies and their staffs are directly involved in the HGP, along with numerous mainland consultants, research organizations, engineering and drilling subcontractors. This project has great potential importance, both for the University and the State, and effective coordination among the wide variety of technological, socioeconomic, and political interests at all educational, private, and governmental levels is essential. The management plan was developed with these diverse interests in mind.

Figure M-I is an organizational chart for Phase II of the HGP. Principal Investigator and Project Director is John W. Shupe, Dean of Engineering. Dr. Shupe serves on the State Environmental Council and was recently appointed by the Governor to establish and chair a Committee on Alternate Energy Sources for Hawaii. He will devote quarter-time to coordination of the HGP.

A co-principal investigator is responsible for the planning and for the direct technical supervision in each of the four research programs: (A) Geophysical Program -- Dr. Augustine S. Furumoto, Professor of Geophysics; (B) Engineering Program -- Dr. Paul C. Yuen, Professor of Electrical Engineering; (C) Environmental-Socioeconomic Program -- Dr. Robert M. Kamins, Professor of Economics; and (D) Dr. Agatin T. Abbott, Professor and Chairman of Geology and Geophysics. Each of these program directors will devote half-time to admini-

HAWAII GEOTHERMAL PROJECT

ORGANIZATIONAL CHART

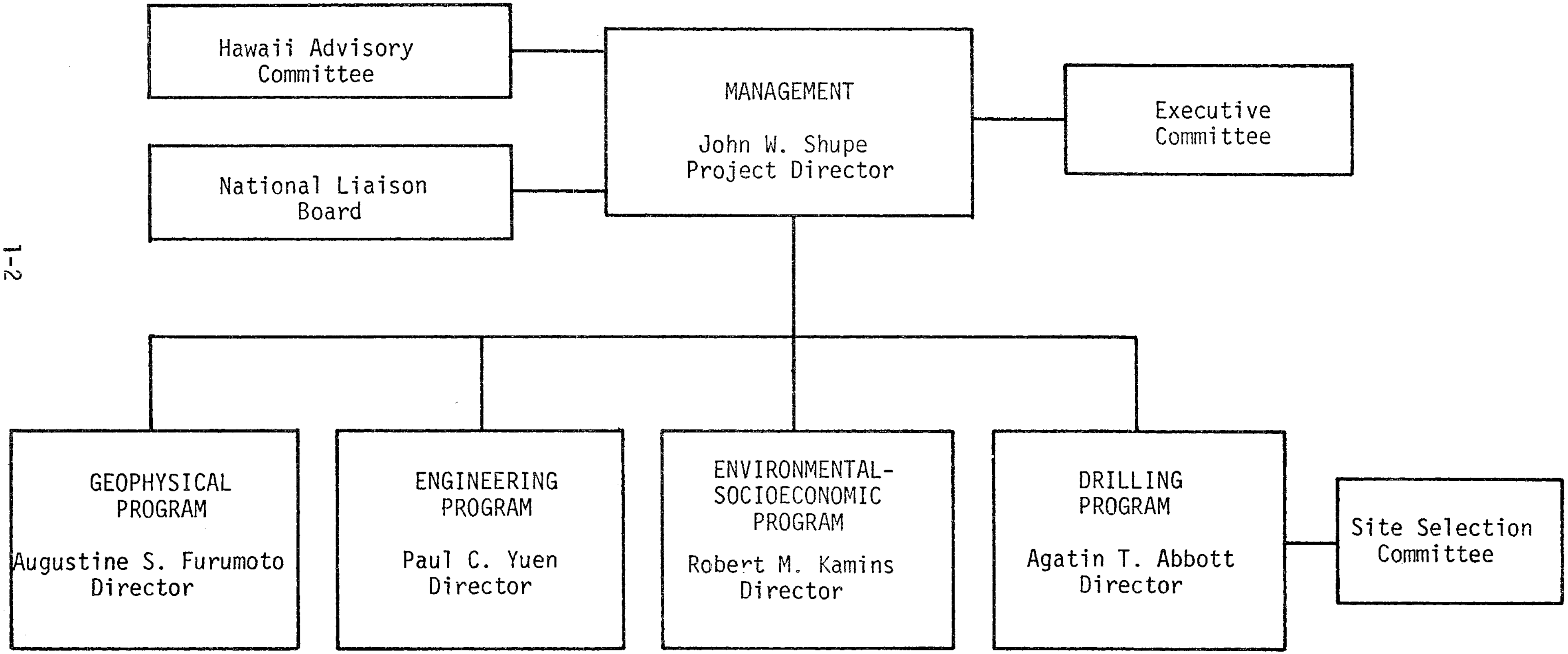



Figure M-I

stration, coordination, and implementation of his respective research program. Although there is a separate budget assigned to each program -- in order to assist in establishing technical and fiscal authority and accountability -- the four co-P.I.'s will meet regularly to help facilitate overall administration of the project.

The HGP Executive Committee consists of the five principal investigators, plus two additional members who will assist the Project Director in assuring the necessary visibility and support throughout the academic community, as well as by the governmental and private sectors: (1) Dr. John P. Craven, Dean of Marine Programs at the University and Director of Marine Affairs for the State of Hawaii; and (2) Dr. George P. Woollard, Director of the Hawaii Institute of Geophysics and a member of the Governor's Science and Technology Advisory Committee. The Executive Committee will: (1) provide technical input in establishing overall goals and objectives; (2) review and approve the research program developed under the leadership of the principal investigators; (3) maintain liaison essential to project support, both on and off campus; and (4) monitor progress of the project. The Project Director assumes full administrative responsibility for implementation of the HGP, and assisting with this effort is Ms. Carolyn Sharma, Administrative Assistant.

To assure that the HGP has both local and national relevance, systematic evaluation and advice will continue to be provided to the Executive Committee and the P.I.'s from numerous sources: (A) the NSF Project Manager; (B) the National Liaison Board; and (C) the Hawaii Advisory Committee. The National Liaison Board (membership list attached) consists of the project leaders of other RANN-supported geothermal programs, along with a few of the national leaders in geothermal research and development. This Liaison Board meets annually in Hawaii to review program progress, to exchange current information

## HGP NATIONAL LIAISON BOARD

Mr. David N. Anderson, Geothermal Officer
State of California Resources Agency
Department of Conservation
Division of Oil and Gas
1416 Ninth Street, Room 1316
Sacramento, California 95814

Mr. Ritchie Coryell, Program Director
Advanced Energy Research and Technology
National Science Foundation
1800 G. Street, N.W.
Washington, D. C. 20550

Dr. George V. Keller, Professor
Colorado School of Mines
Golden, Colorado 80401

Dr. George Kennedy
Institute of Geophysics and
Planetary Physics
University of California, Los Angeles
Los Angeles, California 90024

Dr. James T. Kuwada
Rogers Engineering Company, Inc.
16 Beale Street
San Francisco, California 94105

Dr. Henry J. Ramey, Jr.
Professor of Petroleum Engineering
School of Earth Sciences
Stanford University
Stanford, California 94305

Dr. Robert W. Rex
Republic Geothermal, Inc.
11848 East Washington Boulevard
Whittier, California 90606

Dr. Donald H. Stewart
Battelle Pacific Northwest Laboratories
Post Office Box 999
Richland, Washington 99352

Dr. Donald E. White
Geothermal Research Program
U.S. Department of the Interior
Geological Survey, Geologic Division
345 Middlefield Road
Menlo Park, California 94025

## HGP ADVISORY COMMITTEE

Ms. Sophie Ann Aoki
Life of the Land (Environmental Program)
404 Piikoi Street, Suite 209
Honolulu, Hawaii 96814

Mr. James Bacon, Executive Director
Congress of the Hawaiian People
Suite 351, Alexander Young Building
Honolulu, Hawaii 96813

Dr. John P. Craven, Dean
Marine Programs
University of Hawaii
Holmes Hall 401
Honolulu, Hawaii 96822

Mr. Robert F. Ellis, President
Chamber of Commerce of Hawaii
Dillingham Transportation Building
Honolulu, Hawaii 96813

Mr. Robert H. Hughes
Senior Vice President
C. Brewer and Company, Ltd.
Post Office Box 3470
Honolulu, Hawaii 96801

Mr. Sunao Kido, Chairman of the Board
Department of Land and Natural Resources
State of Hawaii
Post Office Box 621
Honolulu, Hawaii 96809

Mayor Shunichi Kimura
County of Hawaii
25 Aupuni Street
Hilo, Hawaii 96720

Dr. Shelley M. Mark, Director
Department of Planning and
Economic Development
State of Hawaii
Post Office Box 2359
Honolulu, Hawaii 96804

Dr. Richard Marland, Director
Governor's Office of Environmental
Quality Control
550 Halekauwila Street, Third Floor
Honolulu, Hawaii 96813

Dr. Fujio Matsuda, Vice President
Business Affairs
University of Hawaii
Bachman Hall 211
Honolulu, Hawaii 96822

Dr. Howard P. McKaughan
Director of Research
University of Hawaii
Spalding Hall 360
Honolulu, Hawaii 96822

Dr. Paul M. Miwa, Chancellor
University of Hawaii - Hilo Campus
1643 Kilauea Avenue
Hilo, Hawaii, 96720

Dr. Donald W. Peterson
Scientist-in-Charge
U.S. Department of the Interior
Geological Survey
Hawaiian Volcano Observatory
Hawaii National Park, Hawaii 96718

Mr. Herbert M. Richards, Jr.
Vice Chairman, Board of Regents
University of Hawaii
Box 837
Kamuela, Hawaii 96743

Mr. Carl H. Williams, President
Hawaiian Electric Company
Post Office Box 2750
Honolulu, Hawaii 96803

Dr. George P. Woollard, Director
Hawaii Institute of Geophysics
University of Hawaii, HIG 131
Honolulu, Hawaii 96822

on geothermal science and technology, and to advise on future planning and implementation for the HGP.

The Hawaii Advisory Committee (membership list attached) was established to provide interaction with key individuals from industry, government, and the scientific community, whose support is essential to the introduction of geothermal power in Hawaii. Serving on this committee are the Directors of the State Office of Environmental Quality Control and the Department of Planning and Economic Development; the president of the major electric utility company; Director of the County of Hawaii Office of Research and Development; a cross-section of business and industrial leaders of the community; and representatives of citizen groups. This committee meets semi-annually and supplements the Executive Committee in providing the necessary visibility for the HGP, both on and off campus, to assure public and and private support for geothermal power in Hawaii.

The composition and function of the Site Selection and Operations Committee is discussed in the Drilling Program.

The legal fiscal agent for the program will be the Office of Research Administration of the University of Hawaii. The Foundation has engaged in many previous contracts through this agency of the University, so a backlog of experience in administering Foundation contracts and grants already exists.

B. Program Planning And Expenditure Schedule

Figure M-II lists the program and expenditure schedule for each research task throughout both Phases I and II. This one table summarizes the level of activity during each funding period for all of the research tasks, so provides a general overview of funding and program activity up to this date, as well as for Phase II support requested in this proposal.

The three separate sections reflect the research programs during each

# HAWAII GEOTHERMAL PROJECT

## PROGRAM PLANNING AND EXPENDITURE SCHEDULE

| | PHASE I: May 1973 – May 1974 | PHASE I: May 1974 – Jan 1975 | PHASE II: Jan 1975 – Jan 1976 |
|---|---|---|---|
| 1.0 Management | $ 51,865 | $ 11,920 | $ 39,401 |
| Hawaii Advisory Committee | | | |
| National Liaison Board | | | |
| 2.0 Geophysical Coordination & Support | 45,270 | 48,165 | 43,454 |
| 2.1 Photogeologic Surveys | 23,900 | | |
| 2.2 Geoelectric Surveys | 62,626 | 59,126 | 58,709 |
| 2.3 Theoretical and Numerical Modelling, Computational Geophysics, Magnetic and Gravity Surveys | 44,871 | | 33,625 |
| 2.4 Temperature Survey | | 26,289 | 43,124 |
| 2.5 Seismic Studies | 79,135 | 27,532 | 57,000 |
| 2.6 Geochemical Surveys | | 32,884 | 36,718 |
| 2.7 Hydrology | | | 35,107 |
| 2.8 Physical Properties of Rocks | | | 49,191 |
| 3.0 Engineering Coordination and Support | 14,886 | 12,501 | 41,774 |
| 3.1 Geothermal Reservoir Engineering | 44,924 | 39,233 | 122,892 |
| 3.6 Optimal Geothermal Plant Design | 38,533 | 28,293 | 87,781 |
| 4.0 Environmental-Socioeconomic Program Support | 36,690 | 13,701 | 24,824 |
| 4.1 Environmental Aspects | | 11,675 | 42,313 |
| 4.2 Legal and Regulatory Aspects | 9,300 | | 6,800 |
| 4.3 Land-Use and Planning Aspects | | 150 | 11,415 |
| 4.4 Economics | | 17,561 | 46,411 |
| 5.0 Exploratory Research Drilling Program | | 10,729 | 1,205,974 |
| | $452,000* | $339,759 | $1,986,513 |

*Includes $100,000 from State of Hawaii and $100,000 from County of Hawaii

FIGURE M-II

funding period: (1) May 1, 1973 through April 30, 1974 -- $452,000, with $252,000 from NSF and $200,000 from the State and County of Hawaii; (2) May 1, 1974 through December 31, 1974 -- $340,000 from NSF, of which $216,000 has been allocated from FY 1974 and the remaining $124,000 committed from FY 1975; and (3) January 1, 1975 through December 31, 1975 -- $1,986,513 requested from NSF in this proposal.

### C. HGP Personnel Summary

Executive Committee

Agatin T. Abbott, Professor and Chairman of Geology and Geophysics
John P. Craven, Dean of Marine Programs
Augustine S. Furumoto, Professor of Geophysics
Robert M. Kamins, Professor of Economics
John W. Shupe, Dean of Engineering
George P. Woollard, Director of Hawaii Institute of Geophysics
Paul C. Yuen, Associate Dean of Engineering

Geophysical Program

Robert W. Buddemeier, Associate Professor of Chemistry
Pow-Foong Fan, Associate Professor of Geology
Augustine S. Furumoto, Professor of Geophysics
Robert Harvey, Research Associate
Douglas P. Klein, Research Associate
Peter M. Kroopnick, Assistant Professor of Oceanography
L. Stephen Lau, Director of Water Resources Research Center
Murli H. Manghnani, Professor of Geophysics
Roger A. Norris, Research Associate
Ramanan Ramanantoandro, Assistant Geophysicist

Engineering Program

Hi Chang Chai, Professor and Chairman of Mechanical Engineering
Bill H. Chen, Assistant Professor of Engineering (Hilo Campus)
Ping Cheng, Professor of Mechanical Engineering
James C. S. Chou, Professor of Mechanical Engineering

Deane H. Kihara, Associate Professor of Mechanical Engineering
Kah Hie Lau, Assistant Professor of Engineering (Hilo Campus)
L. Stephen Lau, Director of Water Resources Research Center
Patrick K. Takahashi, Assistant Professor of Civil Engineering
Paul C. Yuen, Associate Dean of Engineering

Environmental-Socioeconomic Program
Andrew Berger, Professor of Zoology
Michael J. Chun, Assistant Professor of Public Health
Doak C. Cox, Director, Environmental Center
P. Anders Daniels, Assistant Professor of Meteorology
Nabil A. El-Ramly, Associate Professor of Business Economics
Ruth Gay, Instructor, Botany
Eugene M. Grabbe, Director, State Center for Science Policy & Technology Assessment
Jerry M. Johnson, Assistant Director of Environmental Center
Robert M. Kamins, Professor of Economics
James E. T. Moncur, Assistant Professor of Economics
Richard E. Peterson, Associate Professor of Business Economics
Kap-Kyung Seo, Professor of Business Economics
Sanford M. Siegel, Professor of Botany

Drilling Program
Agatin T. Abbott, Professor & Chairman of Geology and Geophysics
Gordon A. Macdonald, Senior Professor of Geology
Donald W. Peterson, Geologist & Scientist-in-Charge, Hawaiian Volcano Observatory
Charles J. Zablocki, Physicist, Hawaiian Volcano Observatory

Vitae and bibliographies for these participants are listed at the end of each of the program descriptions.

D. Management Program - Phase II

During Phase I of the Hawaii Geothermal Project the Management Program has provided: (1) coordination of activities among the research programs; (2) administrative services to assist with implementation of the research; and (3) promotional efforts at the University, State, and Federal levels to help assure adequate visibility and support for the HGP.

The following organizations (all of which were discussed earlier) were established: (1) the HGP Executive Committee; (2) the Hawaii Advisory Committee; and (3) the National Liaison Board. Operational guidelines and membership lists were developed for these advisory groups, and to date three effective meetings have been held with the Advisory Group, and a most informative evaluation session with the National Liaison Board.

The level of interest in geothermal energy in Hawaii continues to run high. It has received added impetus from the recent energy crisis -- and the resulting lines at the gas pumps. This interest is reflected in continuing State support for geothermal R & D, the most recent of which is the $500,000 allocation for exploratory geothermal drilling.

For Phase II the Management Program will continue with the same responsibilities, while endeavoring to reinforce existing interest and support for the HGP and identify new sources for potential interaction. A joint meeting of the National and Hawaii advisory groups is scheduled for November 1974, with subsequent meetings at the usual intervals throughout 1975.

Close liaison is maintained with all four congressional delegates, who are kept well informed on progress of the HGP. Excellent support, information, and advice is provided by our congressional delegates on any shifts in organizational structure and funding philosophy of federal agencies.

During Phase I, $63,600 was assigned to the Management Program to provide support services, fund the expenses of the Hawaii Advisory Committee and the National Liaison Board, and provide a contingency fund to meet any emergencies that might arise in the research programs. Now that the Project is well established and the program expenses reasonably well defined, it is not necessary to retain a major contingency fund. Therefore, the budget for

Phase II has been reduced to $39,400. Included in the budget renewal is provision for one meeting of the National Liaison Board in Honolulu, and two meetings of the Hawaii Advisory Committee.

# HAWAII GEOTHERMAL PROJECT

## Geophysical Program

Principal Investigator:
Augustine S. Furumoto

## I. INTRODUCTION

The areas of major interest for the Hawaii Geothermal Project are the East and Southwest Rift Zones of Kilauea Volcano and the Southwest Rift Zones of Mauna Loa. For the geophysical program, the East Rift Zone of Kilauea is of prime interest. The East Rift is the testing ground, the research laboratory to find out what geophysical parameters mean in terms of geothermal energy. Surveys in other areas will be interpreted in terms of the results from the East Rift.

The Hawaii Geothermal Project is of more than parochial interest and has many far reaching applications to the geothermal study of other areas. This is clear from a consideration of plate tectonics theory. According to this theory, material from the deeper parts of the mantle upwells along oceanic rift zone crustal spreading center. The ocean floor and lithosphere thus move along in a giant conveyor belt type motion and then plunge back into the mantle at points of crustal convergence marked by island arcs and continental margins marked by oceanic trenches, which are called subduction zones. Most of the volcanoes of the world occur along subduction zones. To explain the Hawaiian volcanic archipelago which occur in the middle of the Pacific Ocean, where there is no subduction zone, but where mantle material nevertheless has broken through the lithosphere and the ocean floor, other mechanisms must be postulated. One is that it represents the consequence of the Pacific crustal plate migrating across a "hot spot" in the mantle. Under this concept there is only one center of volcanism (that now beneath the island of Hawaii), and the archipelago extending up to Midway Island and possibly the Emperor Seamount Chain extending up to the Aleutians mark the trail of crustal migration. Another concept is that the archipelago represents the path of a crustal rift with active volcanism on its leading nose where the rift, as it grows like a crack migrating across a plate glass window, intersects cross cutting transform fault fractures. Either concept would satisfy the increase in age of the archipelago in progressing along it from the island of Hawaii where there is present volcanism. The last, though, would have a point in common with spreading ceters in that volcanism would occur where there is an opening in the crust and reduction in confining pressure. Volcanism ceases when the opening is sealed off by the extruded material plugging the opening and building up sufficient pressure beneath the volcanic pile to stop the flow of lava. This is true of old spreading centers, as well, when the regional stress pattern causes a spreading center to "jump" as in the case of the East Pacific Rise, which is a young feature and was preceded by what is now a "fossil" spreading center located in the middle of the Nazca Plate off Peru. The enechelon pairs of separated major volcanic centers on most of the Hawaiian islands is a strong argument for their having formed at fracture intersections with one fracture system being a migrating one. Another argument is that the high heat flow is confined to the volcanic pile and has no regional extent as might be expected with a "hot spot" having a deep seated source, and another the marked similarity between Hawaiian lavas and those found in association with the crustal plate spreading centers.

The Hawaiian volcanoes could thus bear more than a superficial resemblence to the East Pacific Rise spreading center, and studying Hawaiian volcanoes could have a direct bearing on the study of East Pacific Rise and also on areas as the Salton Sea geothermal area, which overlies the landward extension of the East Pacific Rise beneath the North American continent. As Hawaiian volcanoes are exposed at ground surface, they can be readily studied and experiments performed which would be difficult, if not impossible, elsewhere. The experience gained on the Geothermal Project will thus be applicable to the study of other potential geothermal areas as those on spreading centers as well as island arc subduction zones and other areas of volcanism.

## II. BACKGROUND INFORMATION ON KILAUEA EAST RIFT OF THE PUNA DISTRICT

Kilauea Volcano on the island of Hawaii has two rift zones, the East Rift and the Southwest Rift. The East Rift saw flank eruptions in 1955 and 1960, the Southwest Rift was active in 1971. The East Rift, together with the summit caldera area, has been intensely studied by members of the U.S. Geological Survey. Lately staff members of the Hawaii Institute of Geophysics, University of Hawaii, have carried out surveys along the East Rift.

The East Rift Zone starts off from Kilauea Caldera in a southeasterly direction, and then about 8 or 9 km from Kilauea Crater, the rift zone makes a nearly right angle bend, and heads in a east north east direction to enter into the sea at Cape Kumukahi. Along the rift zone are pit craters, cinder cones, open cracks in the ground and some steaming vents. That part of the rift zone close to Kilauea Caldera is within the Hawaii National Park and this area will not be the subject of investigation of the present proposal. But a 30 km stretch of the rift zone is outside the park boundaries and cuts across what is geographically called the Puna District. Our proposed survey will cover the greater part of the Puna District.

It is impossible to give in this report a good review of past studies in the Puna Area because of the voluminous amount of information. A summation will be presented here and then the present state of the problem will be given.

Geology. The geology of Puna area has been done as part of the study of Kilauea Volcano (Stearns and Macdonald, 1946; Macdonald and Abbott, 1970). It is thought that a platform formed by Mauna Loa lava flows underlies Puna area, and on this platform lie the lava flows and ash deposits from Kilauea. Puna area also has a number of faults parallel to the East Rift Zone.

Geodetic Survey. Comparison of geodetic survey data since 1914 to the present showed that the entire south flank of Kilauea Volcano, of which Puna District is a part, has been displaced seaward for 4.5 meters (Fiske and Kinoshita, 1969). If the seaward slump proceeds at a constant rate, this means a creep of about 8 cm per year. It seems that the slump is more spasmodic in nature.

Gravity Survey. Gravity survey by Kinoshita (1965) showed that the east rift in general had a Bouguer anomaly of about 10-20 mgals above the regional. A survey with closer spacing by Hawaii Institute of Geophysics indicate that the high of the anomaly lies to the north of the rift rather than over it.

Deformation study. From careful surveys in elevation changes, Decker (1974) concluded that the east rift is dipping southward at an angle of $45^{\circ}$. This theory of a dipping rift zone will be checked by our proposed study.

Passive Seismic Observations. Earthquakes in the Puna area occur south of the rift zone, only a few to the north of it. Koyanagi, Swanson and Endo (1972) proposed that the earthquakes are due to the slumping of the south flank. There are times when earthquakes are concentrated in a very small area. These are probably due to magmatic action.

Ward and Gregerson (1973) used a tripartite array of sides 1 to 2 km long to determine hypocenters south of Kilauea Volcano. They concluded that events within 5 to 10 km from the array can be determined accurately. They also found that S waves were poorly recorded. Some focal mechanism solutions were also obtained.

Ground noise surveys have also been carried out. Keller's (1974 ) results claim that 4 hertz ground vibrations are high over areas where electrical surveys showed low resistivity. However surveys carried out by Hawaii Institute of Geophysics do not show such variations, but that the 4 hertz noise dies away from the shoreline.

Active Seismic Survey. Hill (1969) proposed a crustal structure for the Puna area from seismic refraction data. As he did not have close in shots in his survey, he assumed that the first layer had a P-wave velocity of 1.8 km/sec and a thickness of 0.7 km. The second layer had a velocity of 3.1 km/sec and extended from a depth of 0.7 km to 2.3 km. The layer below that had a velocity of 5.3 km/sec.

Magnetic surveys. Magnetic surveys were carried out over Puna several years ago (Malahoff and Woollard, 1968). The results show that there is little magnetic expression over Puna, due to the high temperature of the rift zone.

Electrical Surveys. Keller (1973) carried out a dipole-roving dipole type electrical resistivity survey over the area. The most probable interpretation was a model of two layers overlying a half space of infinite resistivity. The first layer had a thickness of 700 m with resistivity of about 20 ohm-m., the second layer extended from 700 m depth to a depth of about 2.2 km with a resistivity of about 5 ohm-m.

Recent survey by Klein (1974) showed that the near surface rock without water has a resistivity of about 6000 ohm-m and at the water table the resistivity can be as low as 1 ohm-m.

Self potential surveys by Zablocki (1974) made apparent two anomalies on the rift zone, each providing a voltage gradient of several hundred millivolts per 100 meters. The anomalies are positive poles.

Thermal Surveys. There were many wells drilled in the area in search for agricultural water. Temperature measurements made in these wells indicate that higher temperatures occur near the rift zone. Heat flow measurements have not been made.

Geochemical Surveys. Water samples from many of these well have been analyzed for oxygen isotope content. (McMurtry and Fan, 1974). The interpretation of the results is that the groundwater in the region has one through a thermal region at least 200$^{o}$C.

Ongoing surveys. During the months of May to August 1974, several types of surveys will be carried out in the Puna area through NSF Grant GI 38319. Among them are: electrical resistivity surveys, self potential surveys, ground noise surveys, microearthquake surveys, heat flow measurements and geochemical surveys.

## Evaluation and Present Status of Knowledge of Puna Area

The number of surveys carried out in Puna area is impressive and the information we have of the area is large. We should consider the area according to depth, how much we know about Puna to a depth of 2 km and how much knowledge we have of things deeper.

Our information about Puna to a depth of 2 km is extensive. From electrical surveys and seismic refraction surveys, we can conclude that the rocks are very porous to a depth of 2.3 km. Electrically the bulk resistivity of rocks is about 5 ohm-m and the P-wave velocity is 3.1 km/sec. Again from both types of data the porosity of rock seem to be changing at a depth of 700 m. Geochemical study tends to indicate that the source of hot water is the rift zone and that by rapid flow through the permeable rock the hot water is flowing down slope to the sea.

Below 2.3 km our knowledge is less extensive. Seismic velocity is 5.3 km/sec at that depth which indicates very low porosity and permeability. Electrical resistivity is so high that a model of infinite resistivity is appropriate. We do not have enough information from microearthquake data to discuss the situation at depth greater than 2.3 km, but after the planned microearthquake survey of August 1974, we should have more data.

The hypothesis of the rift zone dipping at $45^{\circ}$ as proposed by Decker must be checked. Gravity survey did not give any clue as to the validity or invalidity of that hypothesis.

Slumping of the southflank causes faults to be formed. Some are known by surface traces. But, as in other parts of Hawaii, a good many of the faults are probably undetected because they have ben covered over by lava flows or thick vegetation. The best way to locate such hidden faults are by seismic reflection techniques.

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## III. Results of Geophysical Exploration During the period May 1, 1973 to Present (June 1, 1974), A Progress Report

Upon receipt of Grant GI-38319 from the National Science Foundation and matching grants from the State and County of Hawaii, the geophysical exploration program was initiated. Since the Institute of Geophysics did not have some of the equipment necessary for the proposed work, certain aspects of the proposal such as the Infrared study and the preliminary electrical investigation were contracted out to groups able to start work immediately, since a delay of at least six months could be expected in getting delivery on equipment. At about the same time, George Keller of the Colorado School of Mines, was drilling an exploratory hole in the National Park area of Kilauea Volcano. The information from that drilling project as it progressed provided much useful information of value to the geophysical program.

Because of limitations of funding, only the following types of surveys were planned to be carried out during the first year:

1. Aerial infrared survey covering geologically favorable areas
2. Electrical resistivity surveys of the Puna rift area using the dipole method
3. Electromagnetic surveys of selected areas
4. Microseismic and microearthquake surveys

The aerial photo surveys were the responsibility of Agatin Abbott. The work was contracted to Towill Corporation. Results were available by September 1973.

The dipole electrical resistivity survey for reconnaissance purposes was in by August 1973.

The electromagnetic surveys were under the supervision of Douglas Klein. As all of the equipment had to be built, the field work started late and is still underway at the time of writing of this proposal.

The microearthquake surveys, under the supervision of A.S. Furumoto, got off to a late start because of over eight months delay in getting delivery on equipment. Because of this, the schedule outlined in the original proposal was impossible to maintain. The original proposal planned for surveillance of microearthquakes first, then ground noise surveys. But as instruments for the microearthquake system were not delivered by the manufacturers until February 1974, the ground noise survey was done first, without the benefit of data from the expected microearthquake survey.

Although every economy was made in carrying out the initial phase of surface investigation, including skimping on per diem and borrowing equipment, in January 1974 it became clear that all the proposed cannot be completed with the remaining funds. A decision was therefore made to postpone a major portion of the seismic surveys and redistribute the funds so that the other surveys could be brought to fruition with maximized results. As for the seismic surveys, a reconnaissance ground survey was carried out and the instrument system for microearthquake surveillance was carefully calibrated and field tested on Oahu.

In the following section, short descriptions of the accomplishments of each task are given. For more details, the reader must await the publication of progress reports.

## 1. Photogeologic Survey

Investigator: A. T. Abbott

### Imagery from Infrared Scanning of the East and Southwest Rift Zones of Kilauea and the Lower Portion of the Southwest Rift Zone of Mauna Loa, Island of Hawaii

### INTRODUCTION

From July 31 through August 4, 1973 night time flights for obtaining infrared imagery along the east and southwest rift zones of Kilauea and the southwest rift zone of Mauna Loa were undertaken on the island of Hawaii. Flights were also made on Hualalai and Kohala volcanoes, but because of inconclusive results are not included in this report. Ground control stations had been established during daylight hours several days prior to starting the flight program. Students stationed at the ground central points guided the aircraft on predetermined flight paths by the use of directional lights which were visible to the plane's navigator. Results of the infrared scanning program are considered to be very successful. Events leading up to the final imagery on 8 x 10 color prints will be discussed below.

The sum of $23,900 was designated by the NSF to be expended on aerial photogeologic work on the Hawaii Geothermal Project. Infrared scanning was the only aerial technique employed in this phase.

A firm specializing in infrared surveys, Daedalus Enterprises of Ann Arbor, Michigan was selected as best equipped and experienced in Hawaiian conditions to accomplish the infrared imagery survey. Towill Engineering Corporation of Honolulu provided the aircraft, pilot and navigator and submitted a report with maps and black and white aerial photographic mosaics. These firms earlier the same year had flown paths for Dr. George Keller of the Colorado School of Mines, who was engaged in locating a deep drill hole near the summit of Kilauea.

## FLIGHT PATHS AND DESCRIPTIONS

### (1) East Rift Zone of Kilauea

Two long parallel flight paths were flown along the East rift zone from points outside the boundary of Hawaii Volcanoes National Park to Cape Kumukahi. Shorter paths crossing the two long parallel lines were flown at the intersection of the rift zone with the main highway between Pahoa and Kalapana. Approximately 35 line miles of usable record was obtained. From this the following strips were selected for reproduction in infrared false color imagery:

Three miles of flight paths high on the rift zone at an average ground elevation of 2100 feet provide excellent examples of rift lineation and temperatures aureoles. The DIGICOLOR prints showed a temperature range of 14$^{o}$C to 20$^{o}$C. Numerous sites along the rift showed spots of white color indicating the temperature exceeded the highest range on that temperature set. This is not surprising in view of the fact that wisps of steam are issuing from some of the vents probably as a result of meteoric water coming in contact with residual heat of lavas from the 1966 eruption in this area. Downslope from the steam vents, a fairly extensive area shows a slightly higher surface temperature than its surroundings, by an average of 1$^{o}$C.

The area for the second set of DIGICOLOR prints in the Kilauea east rift zone was selected from a flight path of approximately two miles in length across the area of intersection of the rift zone and the Pahoa-Kalapana highway at a ground elevation of approximately 3000 feet. The temperature range of this path is 16$^{o}$C - 25$^{o}$C or 1.5$^{o}$C per color. Again numerous sites showing white along the rift zone indicate local hot spots and an aureole of decreasing temperatures are distributed outward from the rift. Fine examples of surface temperature zones are demonstrated in this imagery.

(2) Southwest Rift Zone of Kilauea

A flight path 12 miles long was followed from the point of intersection of the western boundary of Hawaiian Volcanoes National Park and the main highway between Kilauea summit to Pahala to a point on the sea coast approximately 4 miles east of Punaluu.

The altitude maintained was about 3000 feet above ground level. Throughout most of the strip a thermal anomaly was evident along the Great Crack. The temperature range on the flight path was 18$^{o}$C - 22$^{o}$C. Of unusual interest on this path is a thermal anomaly in a target-like pattern near the southern end of the Great Crack approximately 1 1/4 miles from the coast line at an elevation of 300 feet above sea level. The target-like pattern is 1200 feet wide, 1600 feet long. The roughly circular pattern of thermal anomaly lies 600 feet northwest of a splinter extension of the Great Crack. The highest temperature within the target area reaches the red color or 22$^{o}$C in two small spots, and within the Great Crack extension, small local spots reach white, or off scale.

The anomaly appears to be associated with the lower slopes along the south side of Puu Kolekole, a prehistoric cinder cone, and with the extension of the Great Crack.

This surface thermal anomaly as registered by infrared scanning imagery should receive careful attention as a potential area for further geophysical investigation and possibly research drilling.

(3) The Southwest Rift Zone of Mauna Loa

A flight path with the total length of approximately 22 miles followed the southwest rift of Mauna Loa from an elevation of approximately 7000 feet above sea level to the tip of South Point. Only the lowest five mile section of this path to the tip of South Point showed any significant thermal anomalies. This portion has been reproduced in DIGICOLOR and prints developed.

The temperature range on one subset is $16^{o}C$ - $22^{o}C$. Thermal anomalies appear along the cliff face of the Kahuku fault as clusters along the base of the cliff and as linear features possibly indicating bedding planes in the lava flows. Numerous spots along the cliff register red and a few local areas show white, or off scale.

The cause of these anomalies is not known at the present time. The Kahuku fault scarp, which reaches 400 feet in height in this area, faces west. Consideration must be given to the possibility that the anomalies result from residual late afternoon solar heat. The imagery was taken at 0030 hours in order to reduce the effect of residual heat. The physical distribution of the warmer areas does not appear to show a pattern that might be caused by residual heating, none the less this factor must be kept in mind.

Another, more intriguing possibility lies in the concept that heat may be rising from depth along the plane of the Kahuku fault and issuing at the base of the cliff and along bedding planes of the lava flows. The Kahuku fault is a major structural feature of Mauna Loa shield volcano. It extends ten miles inland from the coast and has been followed out to sea for a distance of over 15 miles. Depth recordings made on board the R/V VALDIVIA in 1973 while steaming past the extension of the fault 4 miles off shore registered a vertical displacement along the fault plane of 1900 meters.

Further geophysical and geological work should be concentrated in the section of the lower portions of the Kahuku fault. This may have promise as an area in which to locate an array of research drill holes.

Also of interest along the South Point shoreline as registered by the infrared imagery is the temperature distribution in the sea water. Directly offshore a large patch of water shows as a white area indicating that its temperature is greater than 22$^{o}$C. It is not recognized at this time whether this is a bay of warm surface water brought in by ocean currents or wind or whether the warming is caused by some other process.

## 2. Electrical Resistivity Surveys

Investigator: G. V. Keller
Report by: A. S. Furumoto

The electrical resistivity surveys by George Keller were done in June and July 1973 and a report entitled "An Electrical Resistivity Survey of the Puna and Kau Districts, Hawaii County, Hawaii" was submitted by him. The method he used is known as the dipole mapping method. In short, using existing well casings as dipole sources, he caused a large amount of current to flow into the ground, then with a pair of probes the area round the dipole source was surveyed to measure variations in voltage and current. With that, resistivity of the ground between the dipole source and probes is determined. The survey in effect gives an integrated picture of resistivity with respect to depth. Hence the method is a good reconnaissance tool.

The results of the survey came up with two promising areas indicating subsurface low resistivity. Both of these areas lie along the Northeast Rift zone of Kilauea. In Figure 1 the circled area roughly outlines the low resistivity anomaly.

Keller also attempted a depth vs. resistivity interpretation from his data. The profile resulted in a two layer model; the first layer extending from surface to an average depth of 700 m with resistivity about 20 ohm-m; the second layer extending from 700 m to 2300 m depth with resistivity about 5 ohm-m; and below that a half space of very high resistivity. Keller attributed the low resistivity in the second layer to high temperature.

## 3. Electromagnetic Survey

Investigator: D. P. Klein

1. The electromagnetic survey group of the Hawaii Geothermal Project can report the following accomplishments:

   a. Completion of a loop-loop magnetic induction survey in the northeast Puna area.

   b. Development of a deep-sounding wire-loop magnetic induction system.

   c. Reconnaissance of four areas on Hawaii Island (excluding Puna) which have promising geothermal aspects.

   d. Emplacement of 12 electrode pairs for future deep geoelectric sounding on Hawaii Island.

2. The two-loop induction survey in the Puna area was a follow up to the dipole-dipole galvanic survey of G.V. Keller and associates. The results of Keller's survey which warranted further exploration was the possible existence of shallow geothermal regions in the areas outlined by the dashed lines in Fig. 1. High temperature well waters in these areas add support to such a possibility. The two-loop soundings, whose locations are indicated in Fig. 1, were established with the object of locating the extent of the regions of high conductivity, thus potentially hot water, in the upper 100 meters of the crust. The results were negative in this regard. Local conductivity anomalies at stations 18-1, 19-1, 20-1 and station 6-1, and 3-1, 3-2 could be due to heating effects along the East Rift zone or due to increased porosity associated with Rift fissures. However, the existence of shallow high temperature areas of large horizontal extent are not in evidence. It is recommended that detailed "deep" geoelectric surveys be carried out in the anomalous areas mentioned above, under the hypothesis

that these regions are shallow indicators of a wider spread geothermal regions at depth.

3. In view of the need for deeper penetrating equipment a concentrated effort went into the construction of a power source for a time-domain wire-loop induction method. This power source will provide approximately a 20 amp current-step square wave at 1000 VDC. The system is essentially complete except for field tests. The system is solid state and built to withstand rugged field conditions. The expected depth of penetration of this system is about two kilometers.

4. In anticipation of future operations, four areas on Hawaii were examined in detail for survey sites. These areas, indicated on Fig. 2 (Task 2.2, Geoelectric, of the proposal) were chosen with regard to the rift zone location, age of most recent volcanic activity, available drill hole temperature data and the results from the infrared scanning study.

5. Since the effective use of the wire-loop induction technique requires low resistance electrical earth-grounds, 12 electrode pairs were emplaced for the future surveys. Seven of these were emplaced by Sandia Corporation using a technique of air-dropping specially designed inert-missiles. The reason for early emplacement of electrodues is that the contact resistance can be expected to decrease with age due to natural processes causing closer compaction of earth about the electrodes. Although more electrodes will probably be required, at least future surveys can begin with the several good source field sites now established.

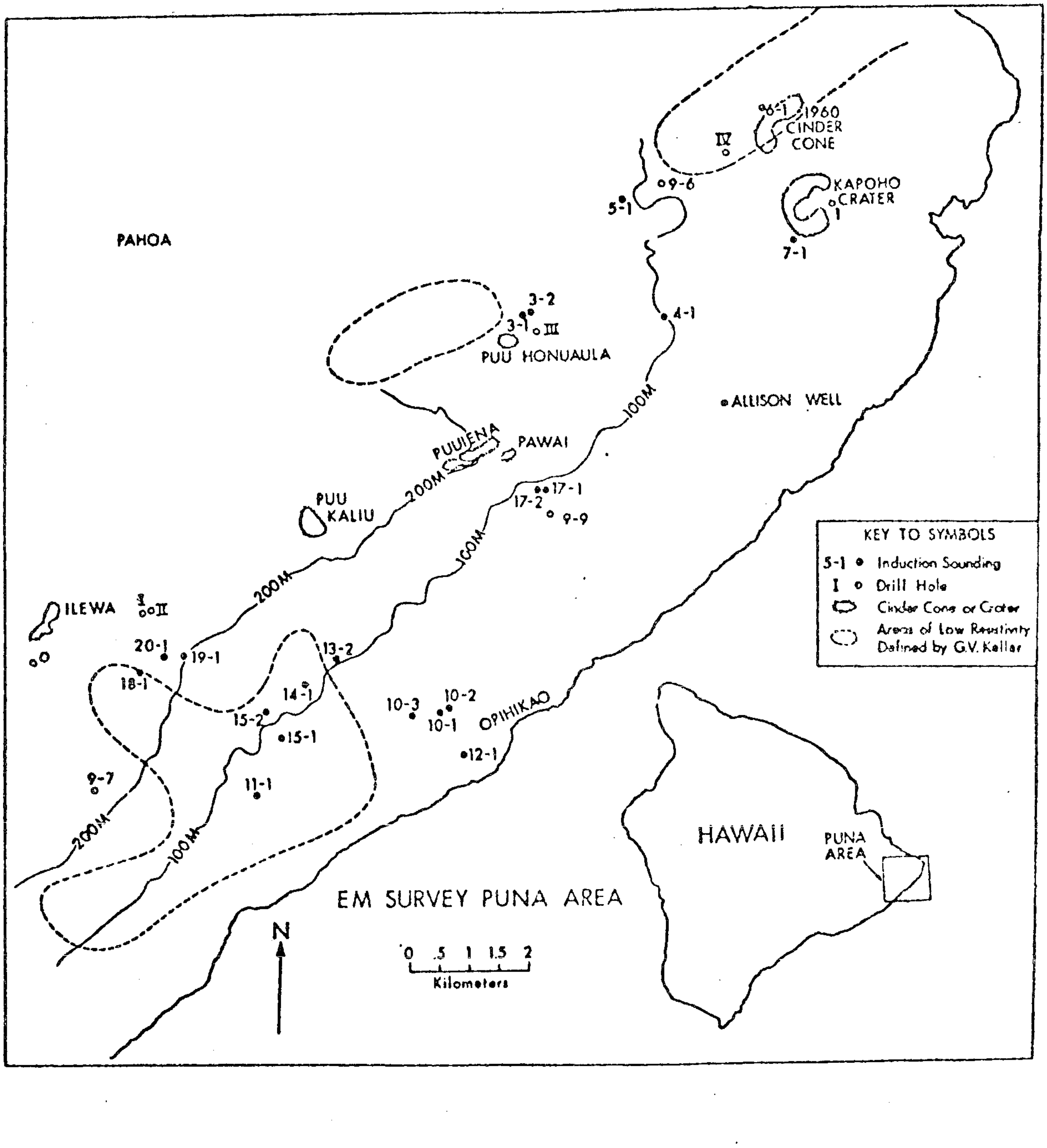


Figure 1

Map of two-loop Magnetic Induction Survey Area

## 4. Microearthquake and Microseismic surveys

Investigator: A. S. Furumoto

Although it was planned to carry out microearthquake surveys during the first year, it was decided to postpone these surveys until the second year. The main reason for this decision was the delay in getting delivery on equipment and that funds were being used up at a higher rate than anticipated in running the other surveys. In the final analysis it was judged better to obtain excellent results from three types of surveys than obtaining marginal data from four types of surveys.

However, the equipment for the microearthquake surveillance program purchased is now assembled and undergoing tests. The seismic surveillance system consists of a central recording station and six satellite stations. At a satellite station seismic signals picked up by geophones are amplified, frequency modulated, and then telemetered by radio to the central recording station. Data is recorded on tape at the central station.

For the microseismic or ground noise survey, a simple system was devised. The instrument package consists of two geophones, an amplifier bank, and a TEAC R-70 cassette tape recorder which can record in FM mode or in direct analog form. The package is small enough to be housed in the backseat of a compact car.

With the above instrument package, the eastern section of Puna district was surveyed on a preliminary basis for ground noise. Two days of recording were made on eight reels of cassettes. For data processing, many techniques were tried; such as digitizing the records followed by power spectrum analysis by computer; use of machine frequency analysis. These were unsatisfactory as sampling or frequency resolution was poor. The best results were obtained by sending the taped signals through narrow band filters and obtaining rectified, averaged power levels. By this technique it was found that the 8 hz ground noise centered around the electrical resistivity anomalies found by Keller. Whether this is also diagnostic of geothermal sources is yet to be determined.

Ground noise surveys are presently being carried out over the Puna area and the southwest rifts of Kilauea and Mauna Loa.

## 5. Other Surveys. 1973-1974

Report by: A. S. Furumoto

In addition to the fore mentioned surveys, several other types of surveys were undertaken.

Although gravity surveys over the Puna area were carried out about a decade ago, the grid was rather course. So, in May 1974 a closely spaced traverse was made across the Puna Rift. Time was available for only one traverse as the work was done in between electrical surveys. Even with the single traverse, a significant bit of information was found. The high positive point of Bouguer anomaly is not over the rift zone but to the north of it. This does not lend support to Decker's postulate that the rift zone is dipping to the south. However this does not contradict Decker as the mass in the rift zone is not much denser than the surrounding rock.

Magnetic surveys by traverses on the ground surface were also done. There was little variation in the magnetic field, an indication that the rift zone material is very hot, above the Curie Point.

Independent of this project, Zablocki of Hawaii Volcano Observatory carried out a self-potential electrical survey in the Puna area. Two anomalies of several hundred millivolts per 100 m were found, coinciding with Keller's low resistivity anomalies. These are encouraging signs. At the present time, technicians and students on this project are assisting Zablocki to complete the self-potential survey of Puna area. Data from this cooperative will be available to the project.

The water in the presently existing wells in Puna area were sampled and were analyzed for oxygen isotope content at the laboratories of University of California at Riverside. The analysis at Riverside were done by a graduate student from this project who traveled to Riverside. The conclusion of the analysis is that the water had a past history of being heated to 200°C or more. This task was carried out under the direction of Dr. P. F. Fan.

As additional funds were promised by the National Science Foundation to continue the program until the end of calendar year 1974, a full schedule of surveys has been planned for the summer months. The Schedule runs as follows:

June

- Self potential electrical survey
- Electrical resistivity survey
- Seismic ground noise survey
- Geochemical survey, oxygen isotope and deuterium

July

- Electrical resistivity surveys
- Laboratory study of convection in porous media, theoretical study and modelling
- Literature survey

August

- Microearthquake surveillance
- Thermal survey of wells
- Electrical resistivity surveys

6. Resulting Publications

The present time is too early for results of the field surveys to see the light of publication. The infrared scanning survey is the only one of the field work that is in publishable form. However, literature survey and compilation of published articles on the Koolau Volcano on the island of Oahu, Hawaii and on the Rabaul Volcano on the island of New Britain, Papua New Guinea, were done and papers on them were presented at the U.S.-Japan Cooperative Science Seminar held in Hilo, Hawaii during the week of February 4-8, 1974. The papers will be published in the Proceedings of the seminar. The authors and titles of publications resulting from the project or supported by the project are:

A. T. Abbott - Imagery from Infrared Scanning of the East and Southwest Rifts of Kilauea and the Lower Portion of the Southwest Rift of Mauna Loa, Island of Hawaii. Proceedings of the U.S.-Japan Science Seminar on Utilization of Volcano Energy, February 1974. Sandia Laboratories, 1974, (in press).

A. S. Furumoto - Geophysical Exploration on the Structure of Volcanoes: Two Case Histories, Ibid. (In Press)

A. S. Furumoto and W. A. Wiebenga - Possible Use of the Rabaul Volcanic Complex as a Source of Energy. Ibid. (In Press)

## IV. PROPOSED WORK FOR 1975

The geophysical program of the geothermal project with funding through NSF GI-38319 is carrying out field surveys in high gear at the present writing of this proposal. As the field surveys will have been completed by September 1974, the present proposal will put emphasis on analysis and interpretation of the field data.

The types of field surveys and study that would be completed are more in number than what had been mentioned in the initial proposals. As data unfolded, different types of surveys were conceived and carried out to check the newly developing picture. The types of surveys being carried out are given below. Each survey involves different kinds of instrument and equipment and different ways of analysis. For example, the several surveys that involve electrical techniques are different from one another and each yields a distinct type of information.

The surveys and studies that were completed or are going on now are the following:

1. Infrared scanning aerial photography
2. Electrical resistivity reconnaissance by dipole-roving dipole method
3. Loop to loop electromagnetic method
4. Depth profiling for electrical resistivity by Schlumberger method
5. Self-potential electrical survey
6. Magnetic surveys on ground surface
7. Gravity survey
8. Seismic ground noise survey
9. Microearthquake epicenter location
10. Geochemical survey, oxygen isotope
11. Geochemical survey, deuterium
12. Thermal survey of wells

13. Convective motion in porous media, analytical and computer study

14. Convective motion in porous media, physical model study

15. Literature survey on geochemistry of Kilauea

The tasks responsible for these surveys with the names of investigators are the following:

Task 2.0 General Services and Coordination

A. S. Furumoto

Task 2.1 Photogeology

A. T. Abbott

Survey (1)

Task 2.2 Electrical Methods

D. P. Klein

Surveys (3), (4), (5),

Task 2.3 Modelling and Computation

R. Norris and A. S. Furumoto

Surveys (6), (7) and office studies (13) and (14)

Task 2.4 Temperature studies of wells

J. Halunen and D. Epp

Survey (12)

Task 2.5 Seismic Studies

W. Suyenaga and A. S. Furumoto

Surveys (8) and (9)

Task 2.6 Geochemistry

P. F. Fan

Surveys (10). (11) and (15)

Survey (2), electrical resistivity survey by dipole-dipole method, was subcontracted to G. Keller of Colorado School of Mines.

Of these, surveys (1), (2) and (3) are completed and final data are in;

surveys (6) and (7) are partially completed; surveys (5), (8) and (10) are being done in the field; surveys (4) and (9) are in the instrument testing stage; surveys (11) and (12) are being planned. The in-office studies (13), (14) and (15) are also presently being carried out.

After the field work during the months of June, July and August 1974, it is imperative that the data be analyzed, interpreted and digested. Even after the field data are in, the best way for processing the data has yet to be sought by trial and error. This takes time. For example, for the two days of field data in seismic ground noise survey, three months were used in finding the optimum system to process rapidly 15 hours of data tape. Various methods, such as digitizing analog records and then performing frequency analysis, were discarded as giving poor sampling. Several types of automatic machine analysis for spectrum were unsatisfactory. The method finally found to be satisfactory was to determine rectified power level at different frequencies by passing the recordings through narrow band pass filters. This example from seismic study shows that time spent in data processing in the office is usually an order of magnitude longer than the time spent in the field.

Also, along with field data, laboratory studies, theoretical studies, computer simulation, physical models must be tried to get the grasp of what is going on. For optimum results field men should cooperate closely with the model studies, in fact, it is best that they participate in it.

Some field programs are being proposed for this year, as drilling data may turn up added information which must be checked against geophysical surveys. Also, the southwest rift of Mauna Loa, which is presently being surveyed, should be examined carefully. A verbal report by A. T. Abbott says that the research vessel VALDIVIA measured the scarp of the rift at a point 4 miles at sea to have a 1900 m drop. Hence we are proposing a thorough geophysical survey of the seaward extension of that rift and other rifts with the University's research KANA KEOKI.

To round out the geophysical and geochemical information on the Puna Area two new tasks have been added to the geophysical program:

Task 2.7 Hydrology

Investigators: R.W. Buddemeier, P.M. Kroopnick, and L.S. Lau

Task 2.8 Physical Properties of Rocks

Investigator: M.H. Manghnani

Task 2.7 will attempt to unravel the hydrology of the Puna area relying mostly on geochemical data. This information is truly needed to understand the hydrothermal system which we are attempting to use for geothermal development.

Task 2.8 will undertake to measure the thermal conductivity of rocks as well as other physical properties of rocks from the Puna area. This is relevant to the program as initial calculations using reasonable temperature distributions and known values of permeability hint that there could be no convective motion of ground water in Puna Area away from the rift zones. Outside of rift zones the criterion of stability is not exceeded. If there is hot water below a depth of 700 m as Keller's reconnaissance survey tends to indicate (cf. previous chapter) then that water was most probably heated by conduction rather than by convective motion.

The geophysical program proposed will be a coordinated program of 8 tasks with 17 different surveys and studies. As the drilling gets underway, all involved will be on hand to assist with their specific area of knowledge and insight.

# HAWAII GEOTHERMAL PROJECT

## ENGINEERING PROGRAM

Principal Investigator:
Paul C. Yuen

### INTRODUCTION

The principal objectives of the Engineering Program are (1) applied research in problem areas related to the extraction of energy from geothermal resources, and (2) planning and design of environmentally-acceptable geothermal power plants. Research during the past period has been in the areas of (1) studies complementary to and in support of the Geophysics Program, and (2) studies of the economical and technological feasibility of different methods of converting heat energy in a geothermal reservoir to electrical energy. Results of the research effort have been reported in three quarterly progress reports published to date, and the following technical memorandum and reports:

1. Modelling of Hawaiian Geothermal Resources, Technical Report No. 1, January, 1974.
2. Warm water Wells on the Island of Hawaii, Technical Memorandum No. 1, January, 1974.
3. Steady State Free Convection in an Unconfined Geothermal Reservoir, Technical Report No. 2, March 15, 1974, by P. Cheng and K. H. Lau, accepted for publication in the Journal of Geophysical Research.
4. Geothermal Reservoir Engineering: State-of-the-Art, Technical Report No. 3, March 15, 1974, by P. Takahashi, B. Chen, and K. Mashima.
5. Regenerative Vapor Cycle with Isobutane as Working Fluid, Technical Report No. 4, June 10, 1974, by J. Chou, R. Ahluwalia, and E. Woo.
6. Numerical Solutions of Isothermal Pumping and Re-injection, Technical Report No. 5, July 1, 1974, by P. Cheng and C. Wong.
7. Effects of Vertical Heat Sources on Free Convection in a Rectangular Geothermal Reservoir, Technical Report No. 6, July 15, 1974, by K. H. Lau and P. Cheng (in preparation).

A more detailed description of the applied research being proposed for the Engineering Program follows.

# PHASE I PROGRESS REPORT

## TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

The geothermal reservoir engineering research team is composed of three sub-task groups: computer modelling, physical modelling, and geothermal well testing and analysis. The three sub-tasks have the goal of predicting the performance of producing geothermal fields. The computer modelling group will use a mathematical model approach, the physical modelling group will scale model a geothermal system, and the testing and analysis group will evaluate existing geothermal and petroleum gas hardware and software techniques with the aim of synthesizing optimal measurement and prediction alternatives.

The organizational plan and personnel responsible for various sub-tasks are depicted in Fig. 3.1-1.

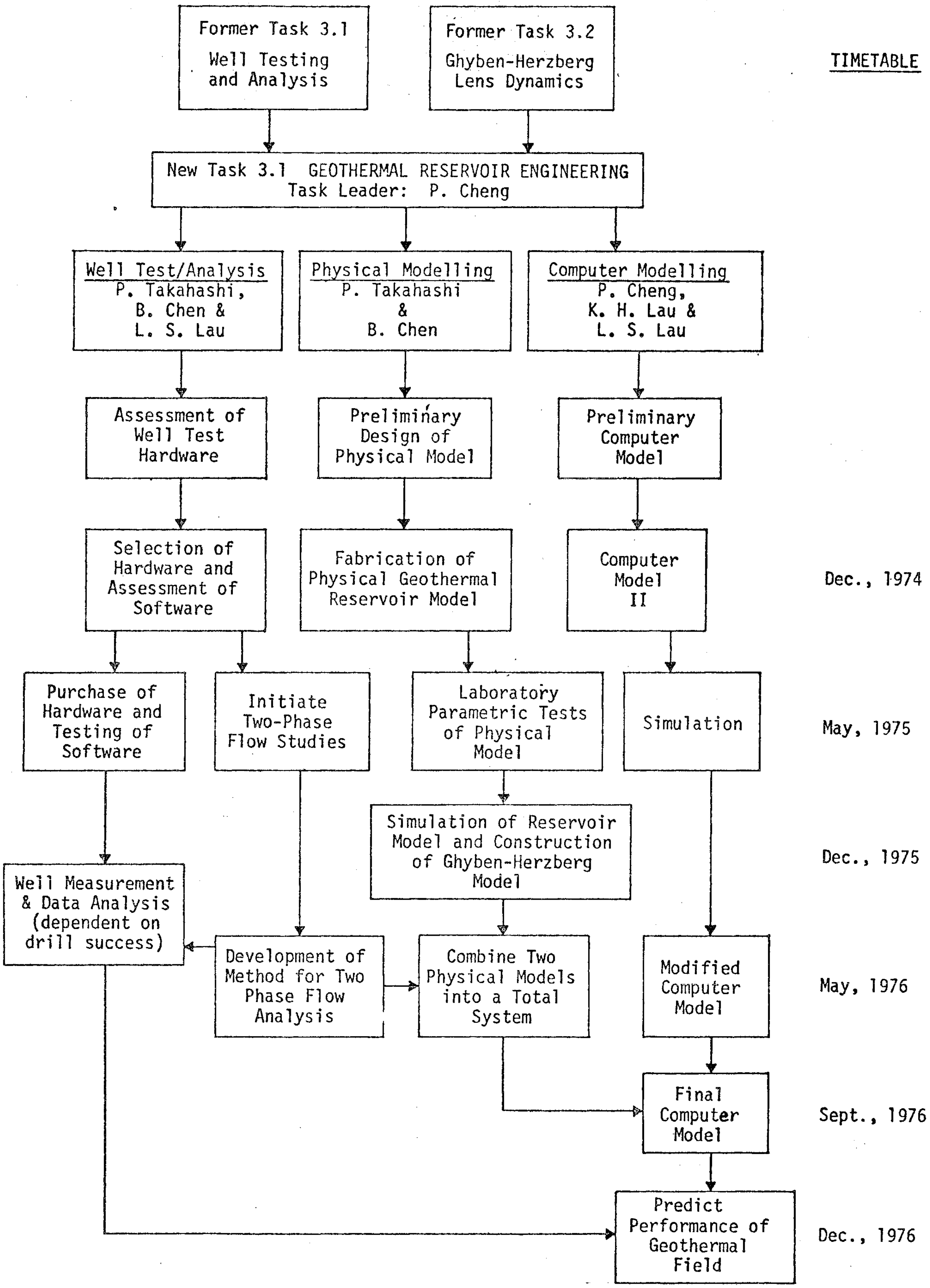


FIG. 3.1-1 ORGANIZATIONAL PLAN FOR THE TASK ON GEOTHERMAL RESERVOIR ENGINEERING

1. <u>Numerical Modelling of Geothermal Reservoirs</u>

Investigators: P. Cheng, K. H. Lau, & L. S. Lau

The primary objectives of the numerical modelling are to predict the performance of geothermal wells under different conditions and to study the environmental impact of the geothermal system, especially the stability of the Ghyben-Herzberg lens when perturbed by the extraction of a fluid from a well below the lens. The results of these studies will aid in the selection of a viable well-site. Specific topics to be investigated are:

1. temperature distribution, heat transfer and fluid flow characteristics of geothermal systems on the island of Hawaii,
2. capacity of a geothermal well,
3. expected life span of a geothermal well under different operating and resource conditions,
4. minimum depth required for a geothermal well so that fresh water will not cone downwards to the well bottom as water is pumped out, and
5. effect of fluid recharge on the performance of a geothermal well.

The aforementioned problems have not been reported in the literature. A realistic simulation of Hawaii geothermal reservoirs must take into consideration the anisotropic property of rock formation; the irregular geometry of boundaries; the dynamics of the Ghyben-Herzberg lens; and the effects of pumping, re-injection, and freshwater recharging. Mathematically, the problem is very complicated since it involves the solution of a set of highly non-linear partial differential equations with non-linear boundary conditions at the water table where its position is unknown. The strategy adopted by the numerical simulation group has been to study simplified situations during the initial phase of the work. These simplified models, which consider different effects one at a time, will aid in a qualitative understanding of the physical processes involved. Furthermore, since the numerical solutions for a more realistic model will probably involve iteration, the results of the simplified models can be used as input data for the first iteration to guarantee convergence of the iteration process. After maturity and expertise have been developed, more realistic models will be considered. The research work will then culminate in the development of a general computer code capable of predicting the performance of a specific geothermal reservoir.

During the first twelve months work has been accomplished in the following three areas:

1. Steady Free Convection in an Unconfined Rectangular Geothermal Reservoir

   A parametric study has been completed which investigates the effects of geothermal heating from below on the movement of seawater, the upwelling of water table, and the pressure and temperature distribution in a rectangular two-dimensional geothermal reservoir. A manuscript entitled, "Steady Free Convection in an Unconfined Geothermal Reservoir" by Cheng and Lau, has been accepted for publication in the Journal of Geophysical Research. The following is a brief discussion on the formulation and the numerical results of the problem. (See Technical Report No. 2 for details of the analysis).

   The Hawaii geothermal reservoir (Fig. 3.1-1A) is idealized as a two-dimensional porous medium bounded on the bottom by a horizontal impermeable wall and on the vertical sides by the ocean

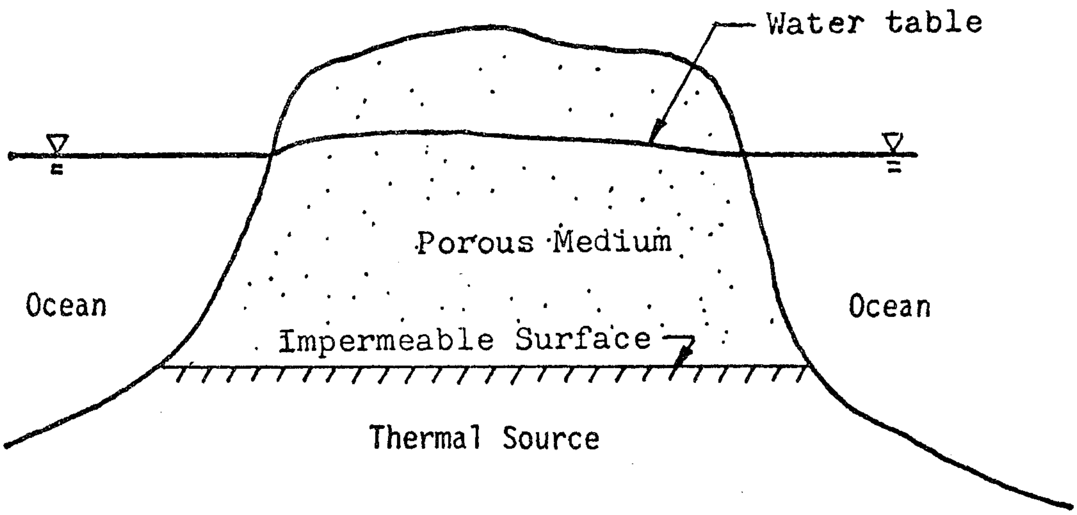


FIG. 3.1-1A UNCONFINED AQUIFER WITH THERMAL SOURCE

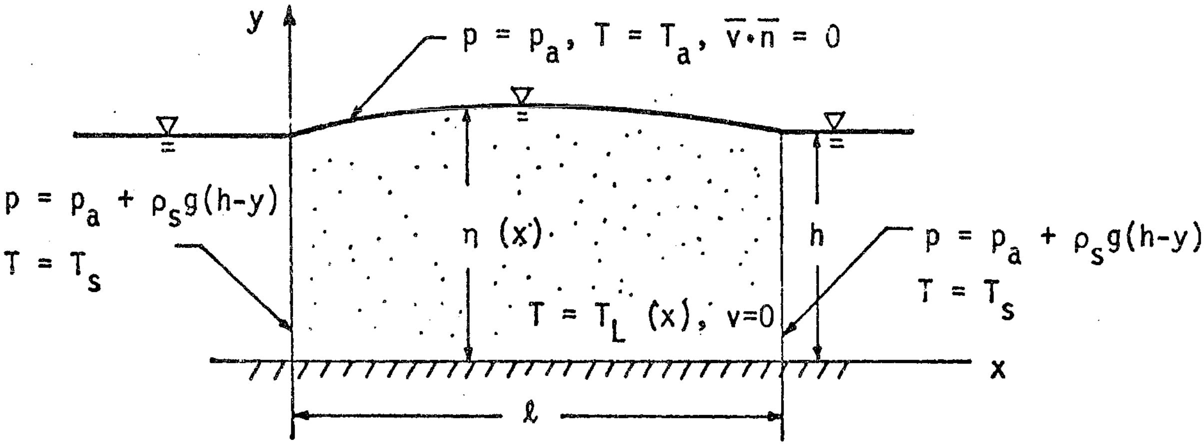


FIG. 3.1-1B RECTANGULAR MODEL OF AQUIFER

(Fig. 3.1-1B). The shape of the water table is not known a priori and must be determined from the solution. To simplify the mathematical formulation of the problem, the following assumptions are made:

A. The flow field is steady and two-dimensional.

B. The temperature of the fluid is everywhere below boiling for the pressure at that depth.

C. The Boussinesq approximation is employed; i.e., density is assumed to be constant except in the buoyancy force term.

D. There is no accretion at the water table; namely, no rainfall.

E. Fluid properties such as thermal conductivity, specific heat, kinematic viscosity, and permeability are assumed to be constant.

F. Ocean is at rest; i.e., the effects of tides are neglected.

With these approximations, the governing equations in terms of dimensionless variables are

$$\frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Y^2} = \epsilon \frac{\partial \theta}{\partial Y} , \tag{1}$$

and

$$\frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} + D \left[ \frac{\partial P}{\partial X}\frac{\partial \Theta}{\partial X} + \frac{\partial P}{\partial Y}\frac{\partial \Theta}{\partial Y} + [1 - \epsilon\Theta] \frac{\partial \Theta}{\partial Y} \right] = 0 , \tag{2}$$

where

$$P \equiv \frac{p - p_a}{\rho_s g h} , \quad \Theta \equiv \frac{T - T_s}{T_c - T_s} , \quad \bar{\eta} \equiv \frac{\eta}{h} , \quad X \equiv \frac{x}{h} , \tag{3}$$

$$Y \equiv \frac{y}{h} , \quad L \equiv \frac{\ell}{h} , \quad \epsilon \equiv \beta(T_c - T_s), \text{ and } D \equiv \frac{\rho_s K g h}{\alpha \mu}$$

with p, T, $\rho$, and $\mu$ denoting the pressure, temperature, density, viscosity; $\alpha$ and K denoting the thermal diffusivity and permeability of the medium; g and $\eta$ denoting the gravitational acceleration and the height of the water table; $T_c$ denoting the maximum temperature of the impermeable surface, and the subscript "s" denoting the condition in the ocean; $\epsilon$ and D are dimensionless parameters.

The boundary conditions along the ocean are given by

$$P\ (0,\ Y) = 1 - Y, \tag{4a}$$

$$P\ (L,\ Y) = 1 - Y, \tag{4b}$$

$$\Theta\ (L,\ Y) = 0, \tag{5a}$$

$$\Theta\ (0,\ Y) = 0. \tag{5b}$$

Along the impermeable surface, the boundary conditions are

$$\frac{\partial P}{\partial Y}\ (X,\ 0) = -1 + \varepsilon\Theta_L\ (X), \tag{6a}$$

$$\Theta\ (X,\ 0) = \Theta_L\ (X), \tag{6b}$$

$$\text{where} \quad \Theta_L\ (X) \equiv \frac{T_L(X) - T_s}{T_c - T_s} \quad \text{with } T_L(X) \text{ prescribed.} \tag{6c}$$

Along the free surface, the boundary conditions are

$$\frac{\partial \bar{\eta}}{\partial X}\frac{\partial P}{\partial X}\ (X,\ \bar{\eta}) - \left[\frac{\partial P}{\partial Y}\ (X,\ \bar{\eta}) + 1 - \varepsilon\ \Theta_a\right] = 0, \tag{7a}$$

$$P\ (X,\ \bar{\eta}) = 0, \tag{7b}$$

$$\Theta\ (X,\ \bar{\eta}) = \Theta_a, \tag{7c}$$

where $\Theta_a \equiv \dfrac{T_a - T_s}{T_c - T_s}$ with $T_a$ denoting the atmospheric temperature,

and $Y = \bar{\eta}(X)$ is the shape of the water table, which is not known a priori, and must be determined from the solution. Since the value of $\varepsilon$ in Eqs. (1-7) is small, the mathematical problem can be simplified based on perturbation method. For this purpose, we now assume that dependent variables be expanded in a power series of $\varepsilon$. Thus we have

$$P\ (X,\ Y) = \sum_{m=0}^{\infty} \varepsilon^m P_m(X,\ Y), \tag{8a}$$

$$\Theta\ (X,\ Y) = \sum_{m=0}^{\infty} \varepsilon^m \Theta_m(X,\ Y), \tag{8b}$$

$$\bar{\eta}(X) = 1 + \sum_{m=0}^{\infty} \varepsilon^m \eta_m(X), \tag{8c}$$

where $P_m(X,\ Y)$, $\Theta_m(X,\ Y)$ and $\eta_m(X)$ are perturbation functions to be determined. Substituting Eqs. (8) into Eqs. (1-7), making a Taylor's series expansion on boundary conditions (7), and collecting terms of like power in $\varepsilon$, we have a set of linear sub-problems.

The governing equations for the zero-order and the first-order problems are respectively the Laplace equation and Poisson equation with nonhomogeneous boundary conditions. In principle they can be solved in closed form by the classical method of separation of variables. However, the numerical evaluation of the resultant expressions in terms of many double and triple Fourier series will be of dubious value because of its slow convergent rate. For this reason we resort to the numerical solution of these linear problems by the finite difference method.

The parameters for the present problem are L the aspect ratio, D the discharge number, and $\varepsilon$ the perturbation parameter. Grid values of pressure, temperature, and stream function are computed for L=4, $\varepsilon$=0.1 with D=50, and 500 for the following three temperature distributions of the impermeable surface:

(1) $\Theta_L = \exp\left[-\left(\frac{X - 2.0}{0.5}\right)^2\right]$,

with a maximum temperature at X=2.0,

(2) $\Theta_L = \exp\left[-\left(\frac{X - 0.5}{0.5}\right)^2\right]$,

with a maximum temperature at X=0.5,

(3) $\Theta_L = \exp\left[-\left(\frac{X - 0.5}{0.1}\right)^2\right]$,

with a maximum temperature at X=0.5.

Comparison of the numerical results for Cases 1 and 2 will show the effect of the location of heat source whereas the comparison of results for Case 2 (a broad heat source) and Case 3 (a narrow heat source) will show the effect of the size of the heat source.

Fig. 3.1-2 shows the contour of the first order perturbation of stream function, $\psi_1$, for Case 1. As is shown in the figure, the fluid particles begin to rise as they approach the point of maximum surface temperature. This is because the density of the fluid becomes smaller as its temperature rises. As the fluid particles rise to a colder region they begin to lose heat and will begin their descending paths when the density becomes the same as that of the surrounding fluid. Fig. 3.1-3 shows the pressure contours for Case 1 with $\varepsilon = 0.1$ and for all values of D. The fact that the pressure contours are almost horizontal indicates that the pressure in an unconfined geothermal reservoir can be approximated by hydrostatic pressure. The effect of discharge number on temperature contours for Case 1 is shown in Fig. 3.1-4. D = 50 corresponds to the case where heat transfer by conduction is predominant whereas D = 500 corresponds to the case where convection heat transfer cannot be neglected. The effect of discharge number on vertical

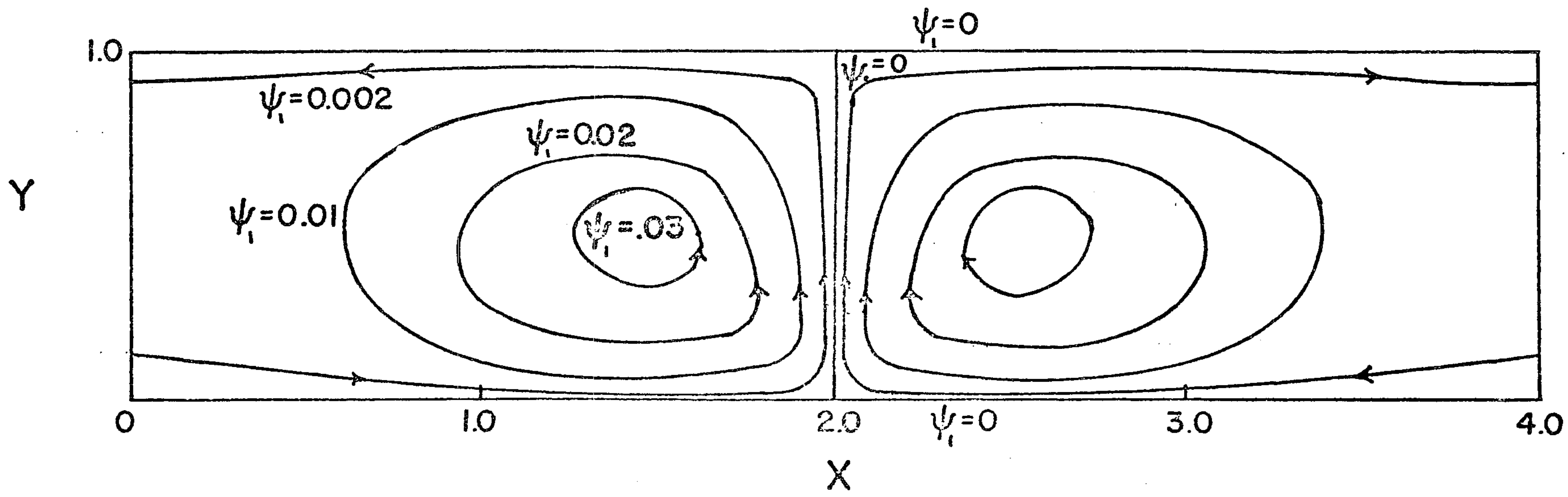


FIG. 3.1-2 CONTOURS OF FIRST-ORDER PERTURBATION FOR STREAM FUNCTION

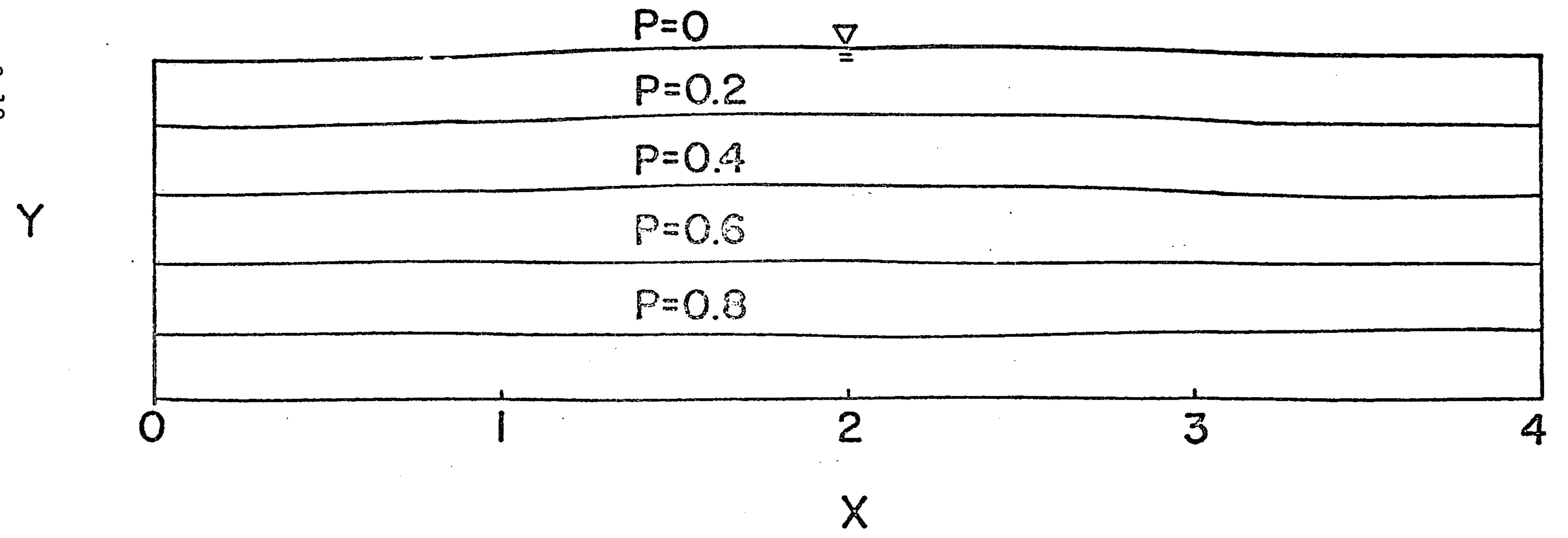


FIG. 3.1-3 PRESSURE CONTOURS FOR CASE 1

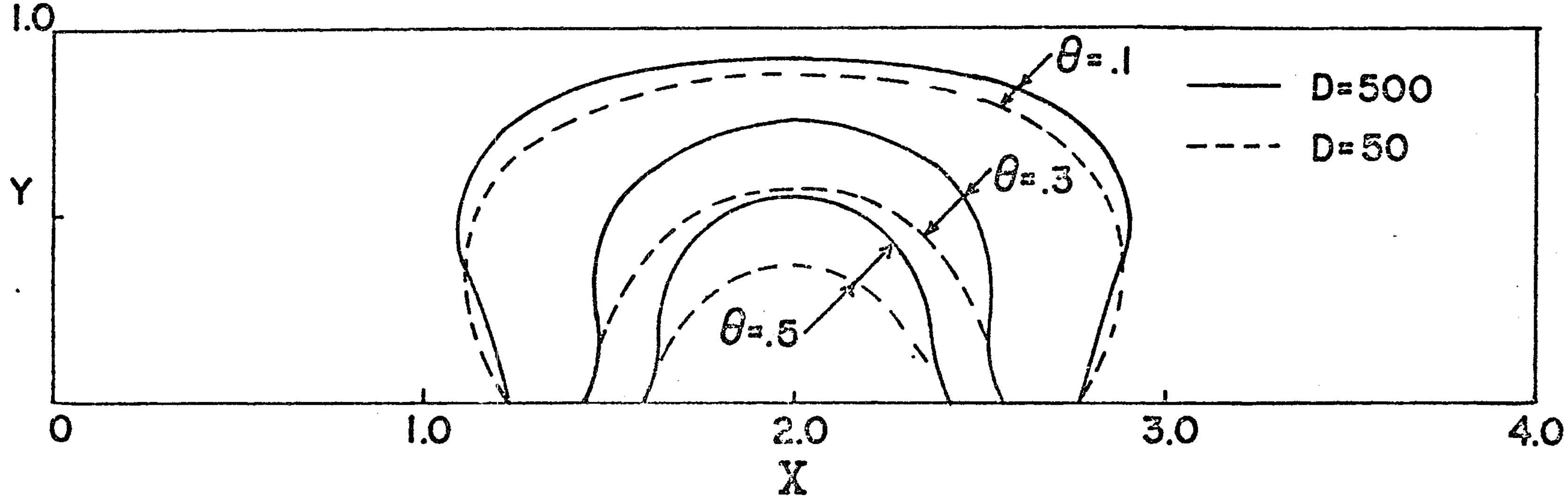


FIG. 3.1-4 EFFECT OF DISCHARGE NUMBER ON TEMPERATURE CONTOURS FOR CASE 1

temperature profiles is shown in Fig. 3.1-5. For locations directly above the point of maximum surface temperature (i.e., at X = 2), temperature is higher for higher value of D. Similar behavior exists in the upper portion of the aquifer. However, in the lower portion of the aquifer, temperature decreases as the value of D is increased. This is due to the inflow of colder seawater in the lower portion of the aquifer and the outflow of warmer seawater in the upper portion of the aquifer.

Figs. 3.1-6A and 3.1-6B show the effect of location and the size of heat source on $\eta_1$, the first order perturbation function for the shape of water table. To the first-order approximation the upwelling of water table is given by $\epsilon\eta_1$, and is independent of D. The amount of upwelling depends on the vertical temperature gradient of the porous medium and the temperature distribution of the impermeable surface. The size and the location of the heat source have a strong influence on the amount of upwelling of water table. The maximum value of $\eta_1$ is approximately 0.08 at X = 2 for Case 1 (Fig. 3.1-6A). For a heat source near the ocean (Fig. 3.1-6B), it is interesting to note that the location of maximum water table height is not necessarily located directly above the point of maximum temperature of the impermeable surface. In fact, the position of maximum value of $\eta_1$ moves inland as the size of the heat source is increased.

It is estimated that the value of D for Hawaii geothermal reservoirs will probably be much higher than D = 500. Consequently, the numerical results do not really correspond to a realistic situation. However, since temperature distribution increases as

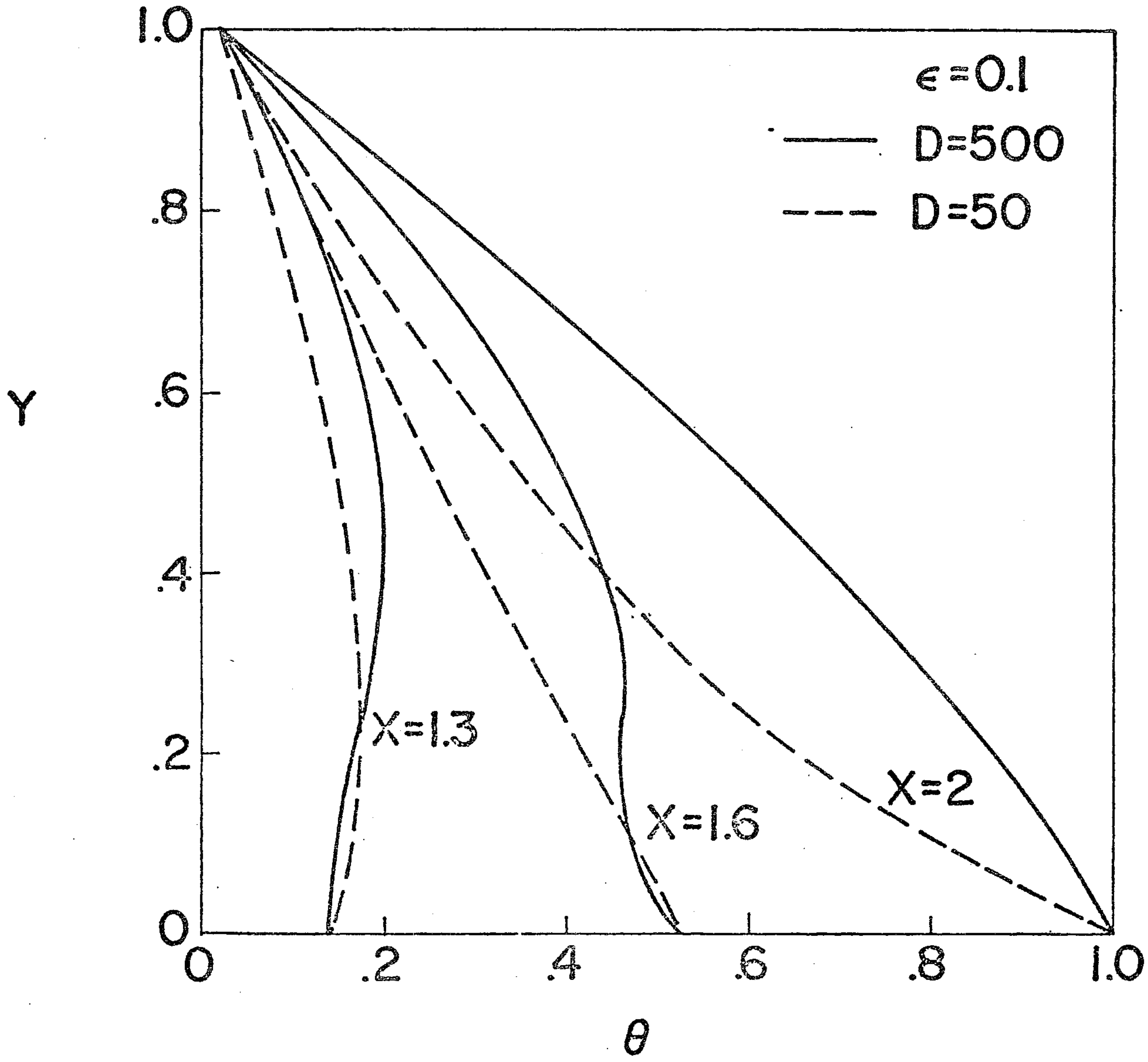


FIG. 3.1-5 EFFECT OF DISCHARGE NUMBER ON VERTICAL TEMPERATURE PROFILES FOR CASE 1

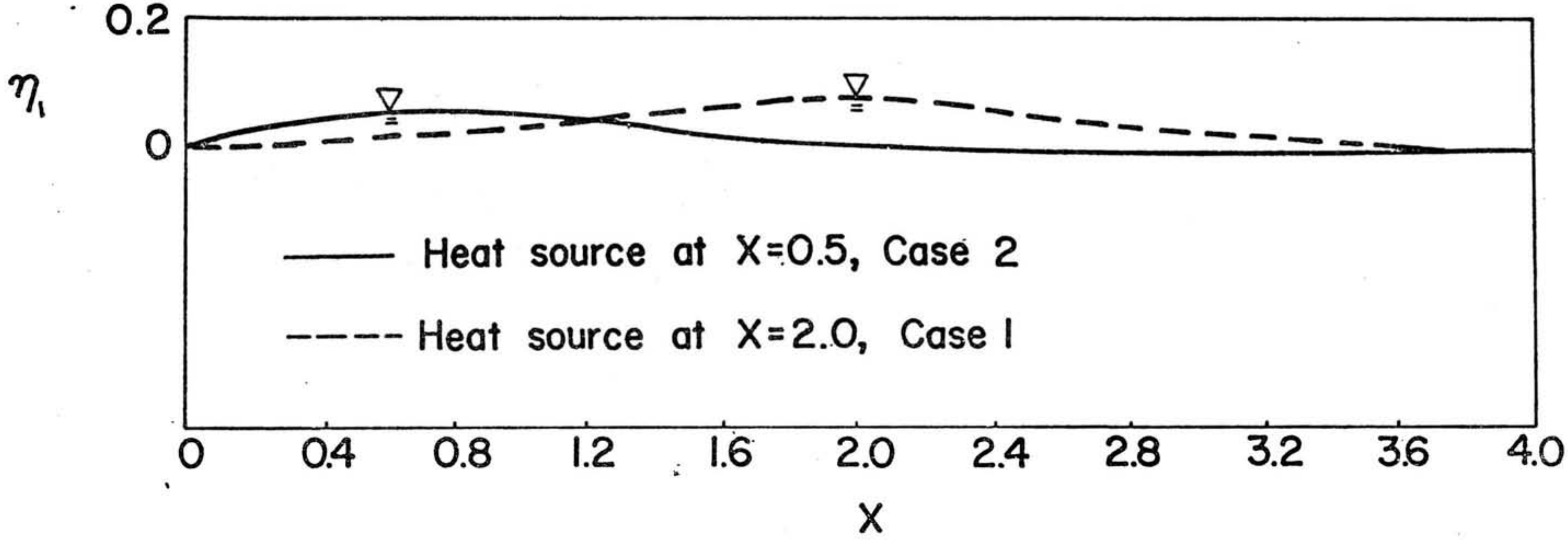


FIG. 3.1-6A EFFECT OF THE LOCATION OF HEAT SOURCE ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

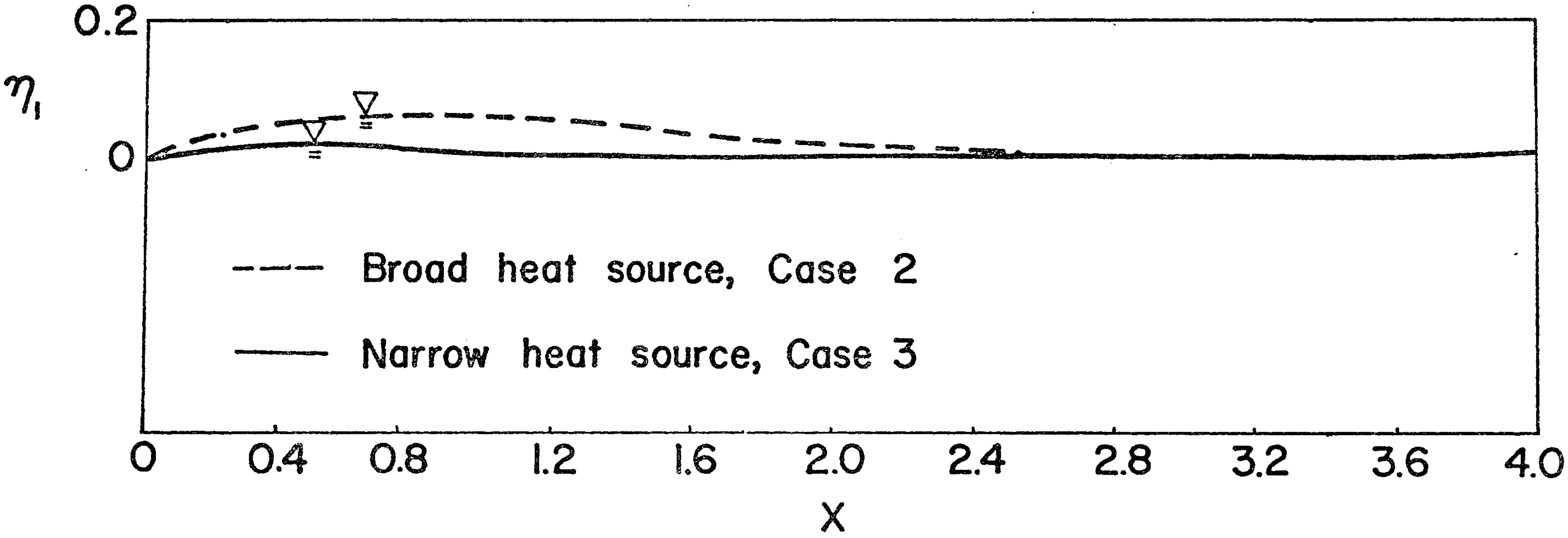


FIG. 3.1-6B EFFECT OF THE SIZE OF THE HEAT SOURCE ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

as D increases, the numerical results do give a qualitative, and yet conservative estimation. Thus, it can be concluded that (1) for a geothermal reservoir 1 mile deep with a heat source at 800°F and half mile in diameter, hot brine at 400°F can be found at half a mile below sea level if the drilling site is at the top of the heat source, (2) while the size of the heat source has an important effect on the temperature distribution in the reservoir, the location of the heat source has a small effect on the temperature distribution, (3) as a result of geothermal heating, cold seawater moves inland from the lower portion of the reservoir and warm water flows into the ocean from the upper portion of the reservoir, (4) heat transfer by convection is important in geothermal reservoirs. Thus the prediction of temperature distribution based on heat conduction will be in serious error, (5) the convection of heat is more efficient vertically than horizontally. This implies that the drilling site must be within the maximum temperature zone of the hot rock, (6) pressure in unconfined geothermal reservoirs can be estimated based on hydrostatic pressure, and (7) the upwelling of the water table is in the order of 100 feet for a reservoir of 1 mile in depth. The upwelling of water table as a result of geothermal heating is predicted analytically for the first time.

The perturbation method is used in the present analysis. The major advantages of the application of the method to the present problem are (1) the problem becomes linear and the difficulty in the non-convergence of iteration associated with the numerical solution of non-linear finite difference equations does not exist,

(2) the unknown position of the water table is explicitly determined from the first-order problem, thus the usual practice of the iteration of position of water table is avoided, and (3) a clearer physical picture emerged with regard to the driving forces and the role played by various parameters in heat transfer and fluid flow characteristics in a geothermal reservoir.

2. <u>The Effects of Vertical Heat Sources on the Upwelling of Water Table</u>

The perturbation approach discussed earlier was extended to investigate the effect of vertical heat sources on the upwelling of water table. The purpose of the analysis is to assess in a qualitative manner whether the upwelling of water table of 2000 feet above sea level reported by Keller [private communication] is due to vertical heat sources.

Suppose a dike exists in the reservoir as shown in Fig. 3.1-7A with the idealized situation shown in Fig. 3.1-7B. The governing equations are given by Eqs. (1-2). In addition to boundary conditions given by Eqs. (4-7), the boundary conditions on the dike are

$$\theta(X_{S_1},Y) = \theta_S \quad , \qquad Y \leq Y_S \qquad (9a)$$

$$\theta(X_{S_2},Y) = \theta_S \quad , \qquad Y \leq Y_S \qquad (9b)$$

$$\frac{\partial P}{\partial X}(X_{S_1},Y) = 0 \quad , \qquad Y \leq Y_S \qquad (9c)$$

$$\frac{\partial P}{\partial X}(X_{S_2},Y) = 0 \quad , \qquad Y \leq Y_S \qquad (9d)$$

$$\frac{\partial P}{\partial X}(X,Y_S) = -1 + \varepsilon\theta_S \quad , \qquad X_{S_1} \leq X \leq X_{S_2} \qquad (9e)$$

$$\theta(X,Y_S) = \theta_S \quad , \qquad X_{S_1} \leq X \leq X_{S_2} \qquad (9f)$$

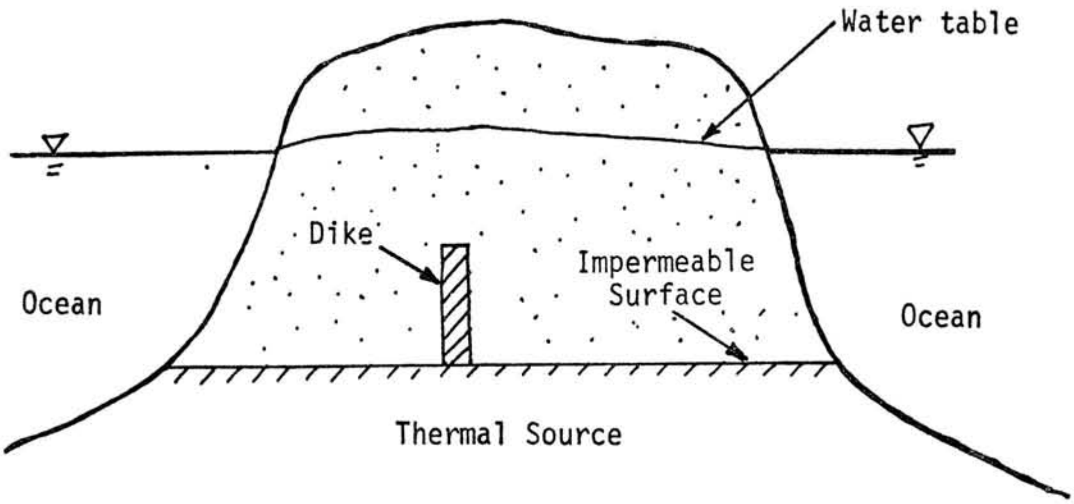


FIG. 3.1-7A UNCONFINED AQUIFER WITH A VERTICAL DIKE

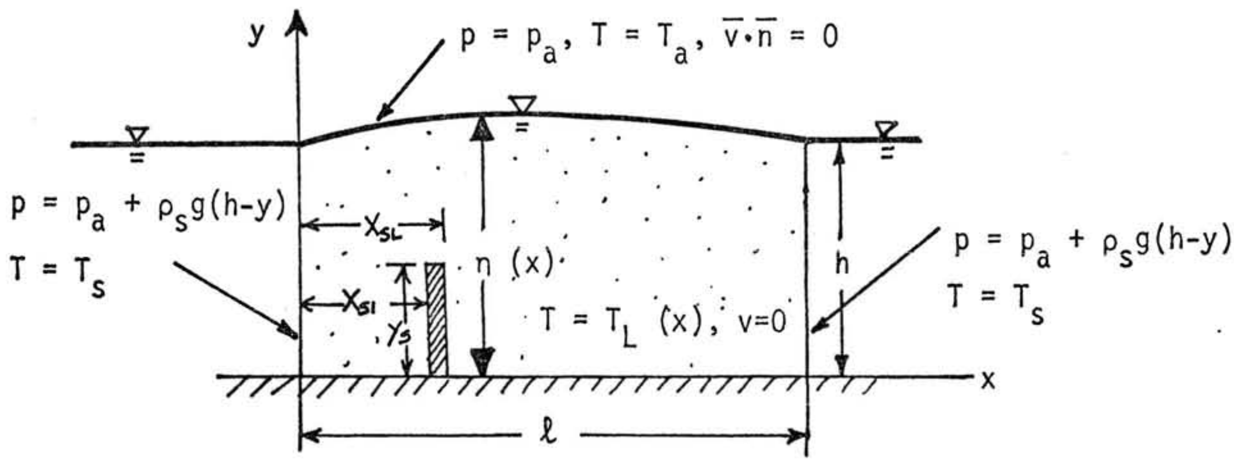


FIG. 3.1-7B IDEALIZED RECTANGULAR MODEL OF AQUIFER WITH A VERTICAL DIKE

where $\theta_S$ is the prescribed dimensionless temperature of the dike. As a result of the perturbation technique described earlier, a set of linear equations is obtained. The resultant equations can then be solved numerically based on the finite difference method. Computations were carried out for the following two cases:

A. Vertical heating only

$$\theta_S = 1 \ , \qquad 0 \le Y \le 0.5 \ ,$$

B. Horizontal and vertical heating

$$\theta_L(X) = \exp[-(\frac{X-2}{0.5})^2] \ , \qquad 0 < X < 1.9, \quad 2.2 < X < 4$$

$$\theta_S = 1 \ , \qquad 0 \le Y \le 0.5, \quad 1.9 \le X \le 2.1$$

Results of these computations along with previous results for horizontal heating are compared in Figs. 3.1-8, 3.1-9, 3.1-10. Fig. 3.1-8 shows the contours of stream functions for Cases A, B, and C where C referred to the previous results obtained in Technical Report No. 2. It is shown that the stream functions of the three cases exhibit similar behavior. The comparison of temperature contours for the three cases with $D = 500$ and $\varepsilon = 0.1$ are plotted in Fig. 3.1-9 where it is shown that hot water at shallow depth is possible whenever there is a hot vertical heat source. The effects of vertical and horizontal heating on the upwelling of water table are shown in Fig. 3.1-10 where it is shown that the amount of upwelling increases for a vertical source. However, the upwelling of 2000 feet seems to be unlikely. A manuscript covering this work is now under preparation, and will be submitted for publication in a journal.

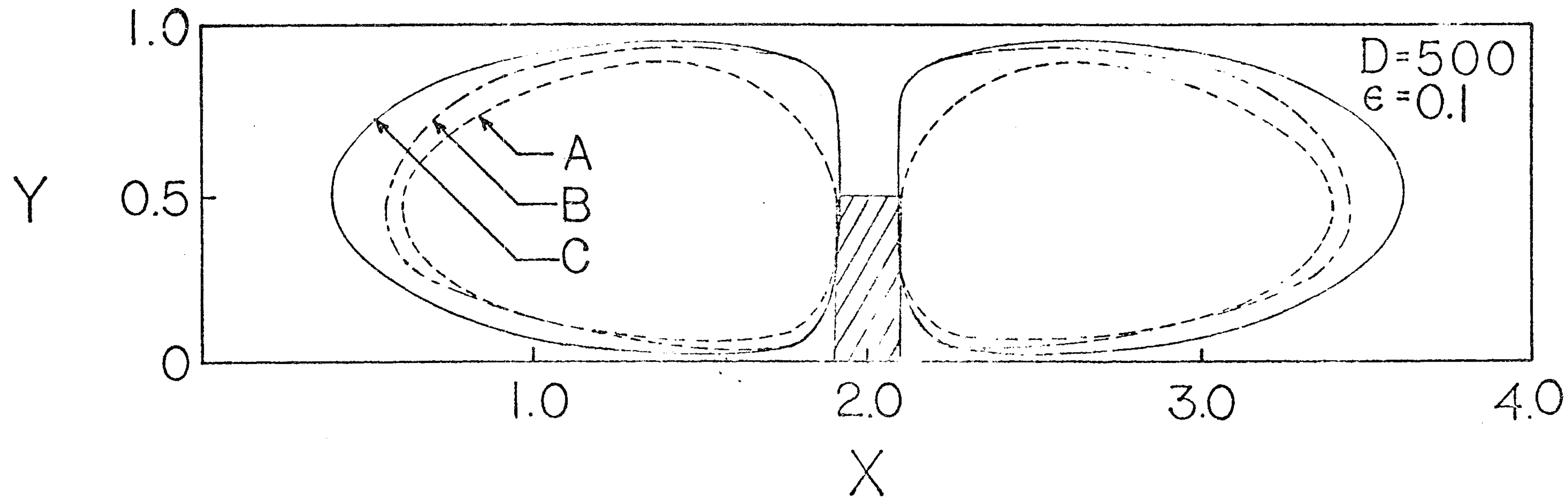


FIG. 3.1-8 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON STREAM LINES

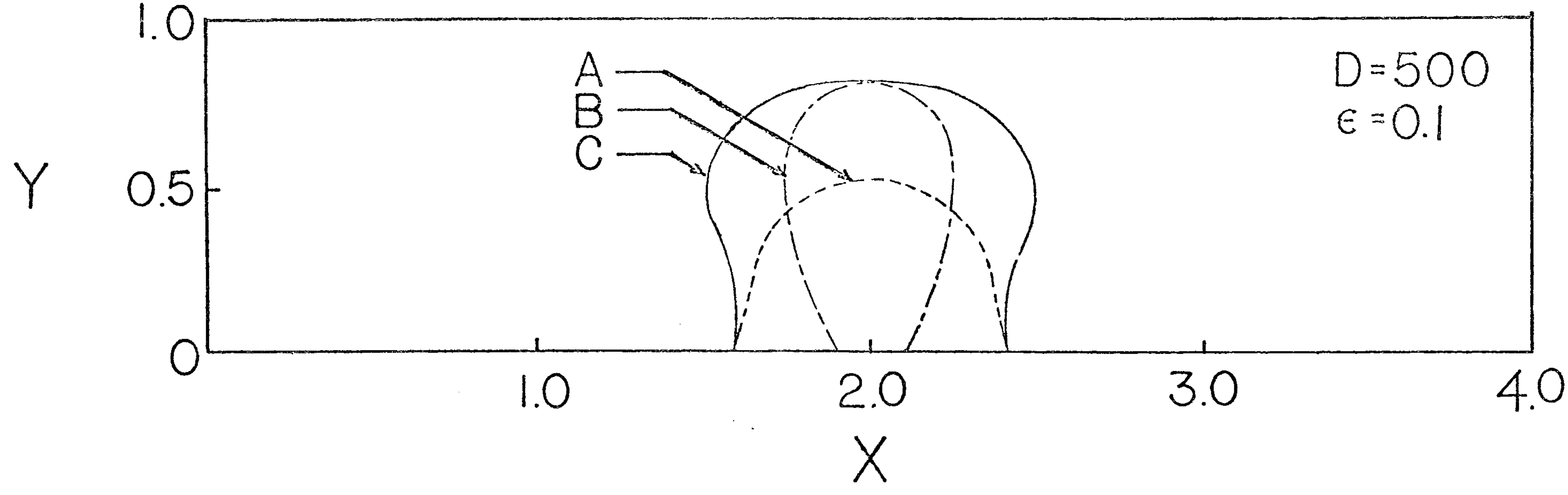


FIG. 3.1-9 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON TEMPERATURE CONTOURS

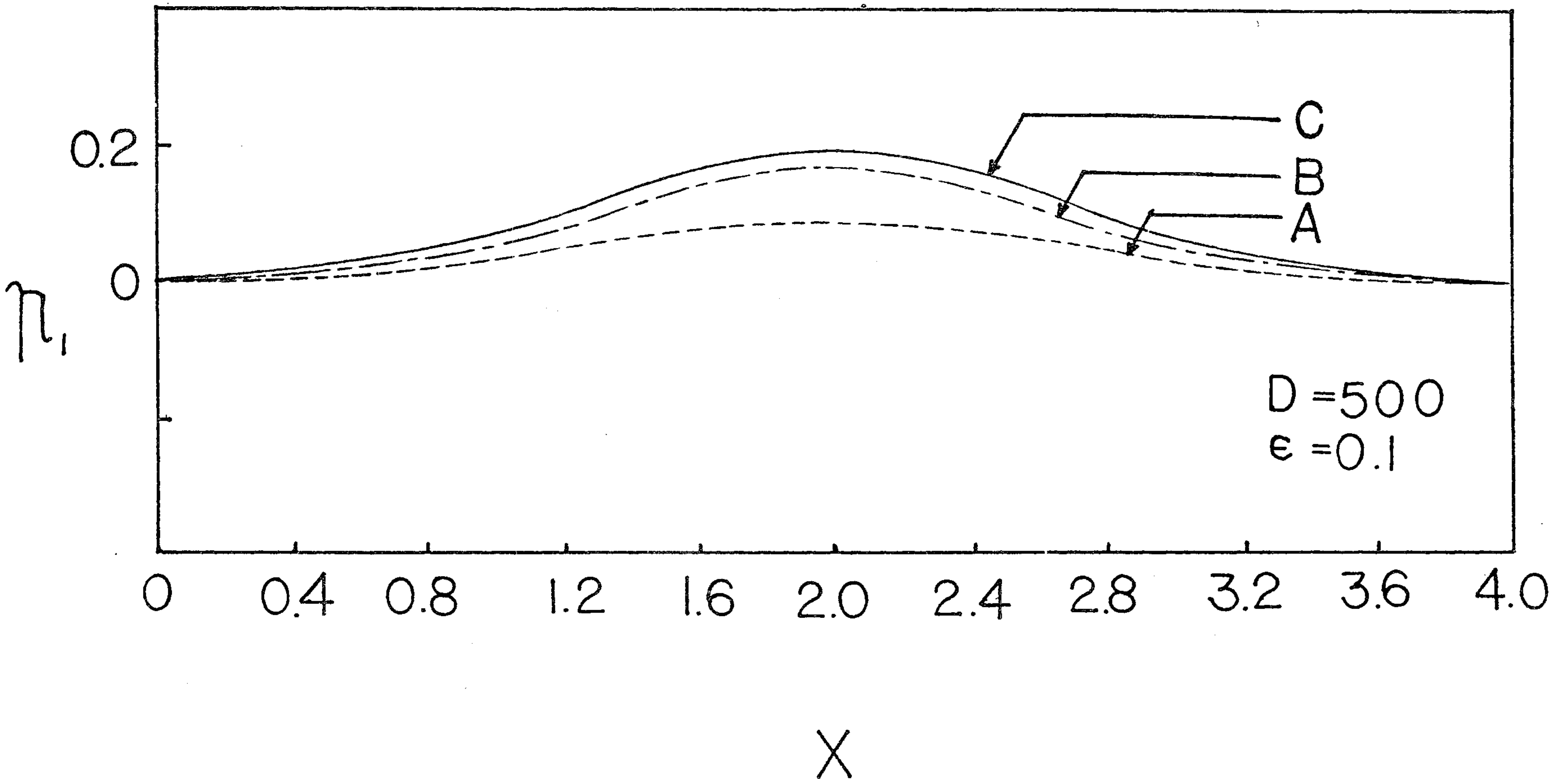


FIG. 3.1-10 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

## 3. Heat Transfer and Fluid Flow Characteristics in an Axisymmetric Geothermal Reservoir

To have a qualitative understanding of the three-dimensional effects of seepage from the ocean on the temperature distribution in geothermal reservoirs, a study has been undertaken for the idealized case of an axisymmetric configuration. The formulation of the problem is similar to Eqs. (1-8) except that they are written in cylindrical coordinates. Numerical computations for $L = 4$, $D = 500$, and $\varepsilon = 0.1$ were carried out. The comparison of temperature contours and vertical temperature profiles between an axisymmetric reservoir and a rectangular one is shown in Fig. 3.1-11 and 3.1-12 where solid lines are for axisymmetric reservoirs and dotted lines are for rectangular ones. It is shown in these figures that temperature in a rectangular reservoir is considerably higher than that in an axisymmetric reservoir due to the three-dimensional seepage effect. Consequently, the upwelling of water table due to geothermal heating is smaller for axisymmetric reservoirs than that of rectangular reservoirs as is shown in Fig. 3.1-13.

In addition to the three problem areas discussed above, work has been initiated on the problems of pumping and reinjection in rectangular reservoirs, and on the finite element formulation of free convection in geothermal reservoirs with irregular boundaries.

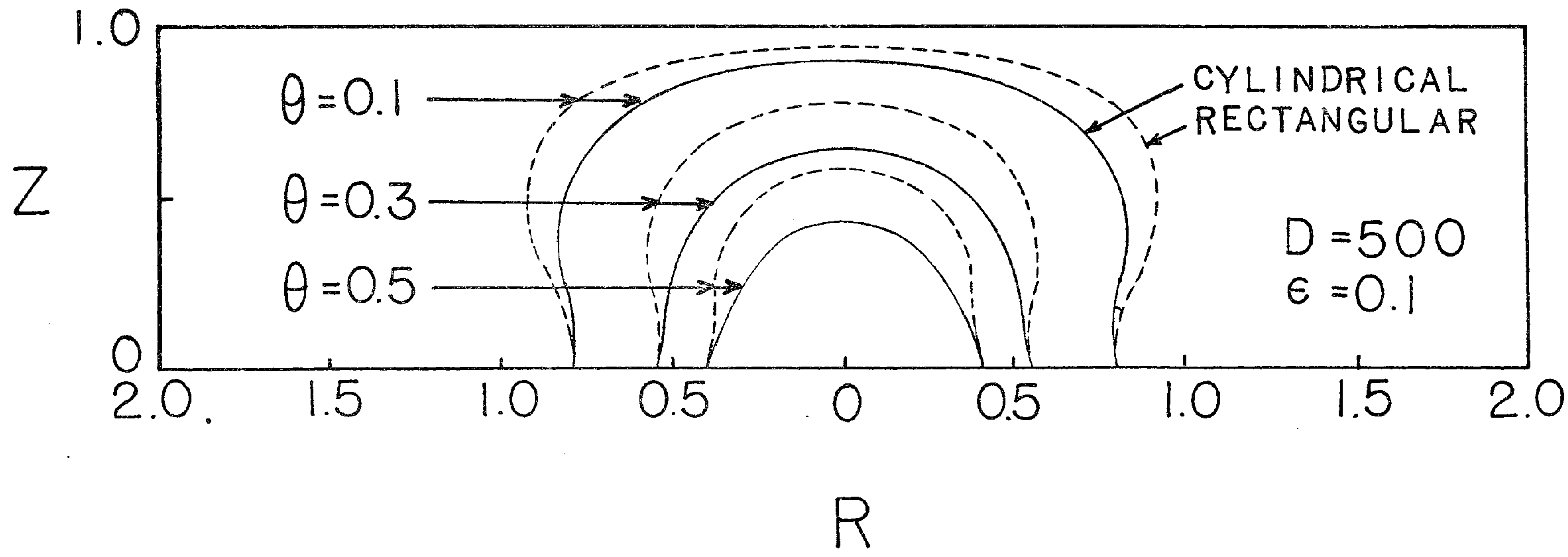


FIG. 3.1-11 EFFECT OF CONFIGURATION OF RESERVOIR ON TEMPERATURE CONTOURS

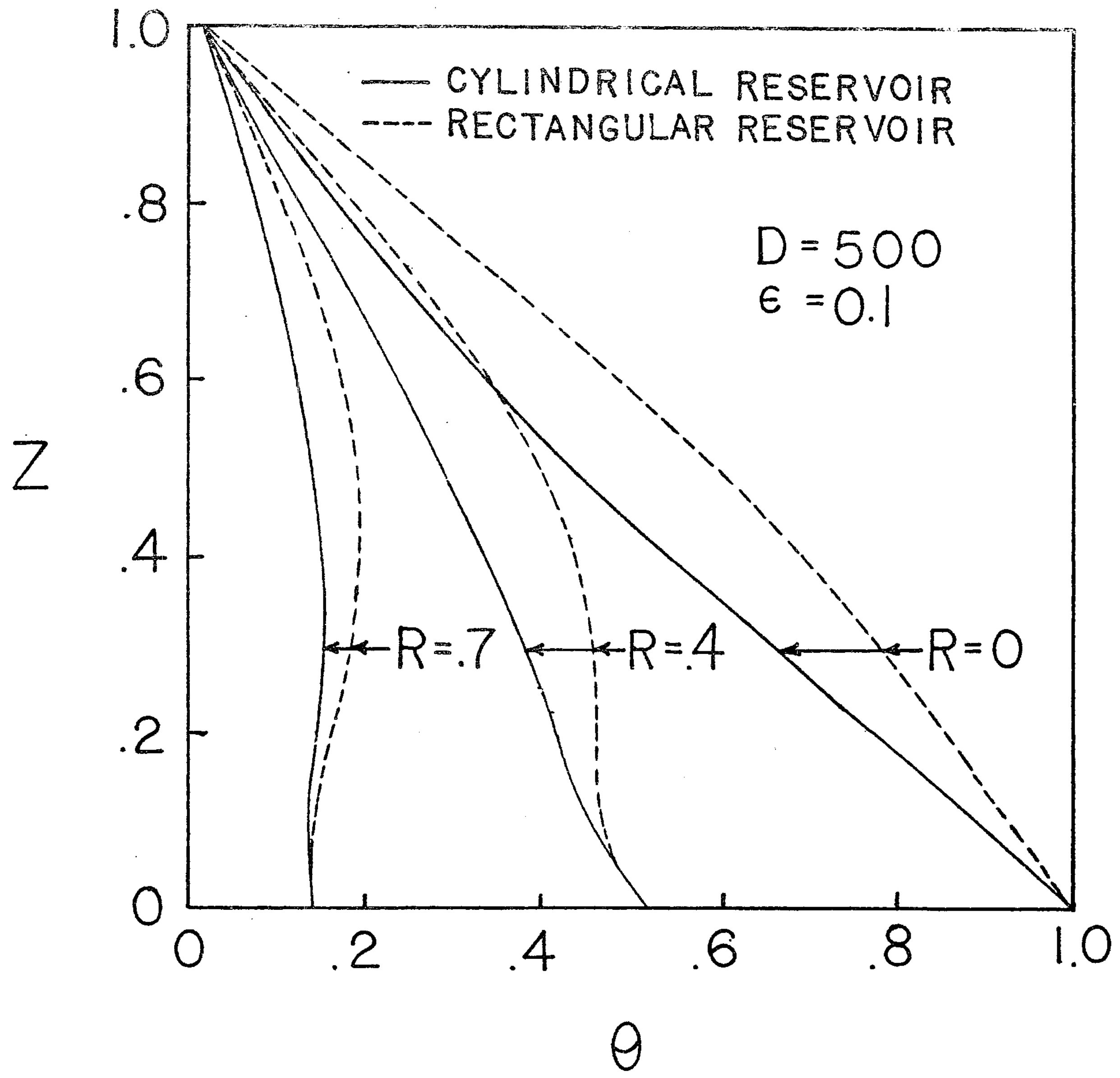


FIG. 3.1-12 EFFECT OF CONFIGURATION OF RESERVOIR ON VERTICAL TEMPERATURE PROFILES

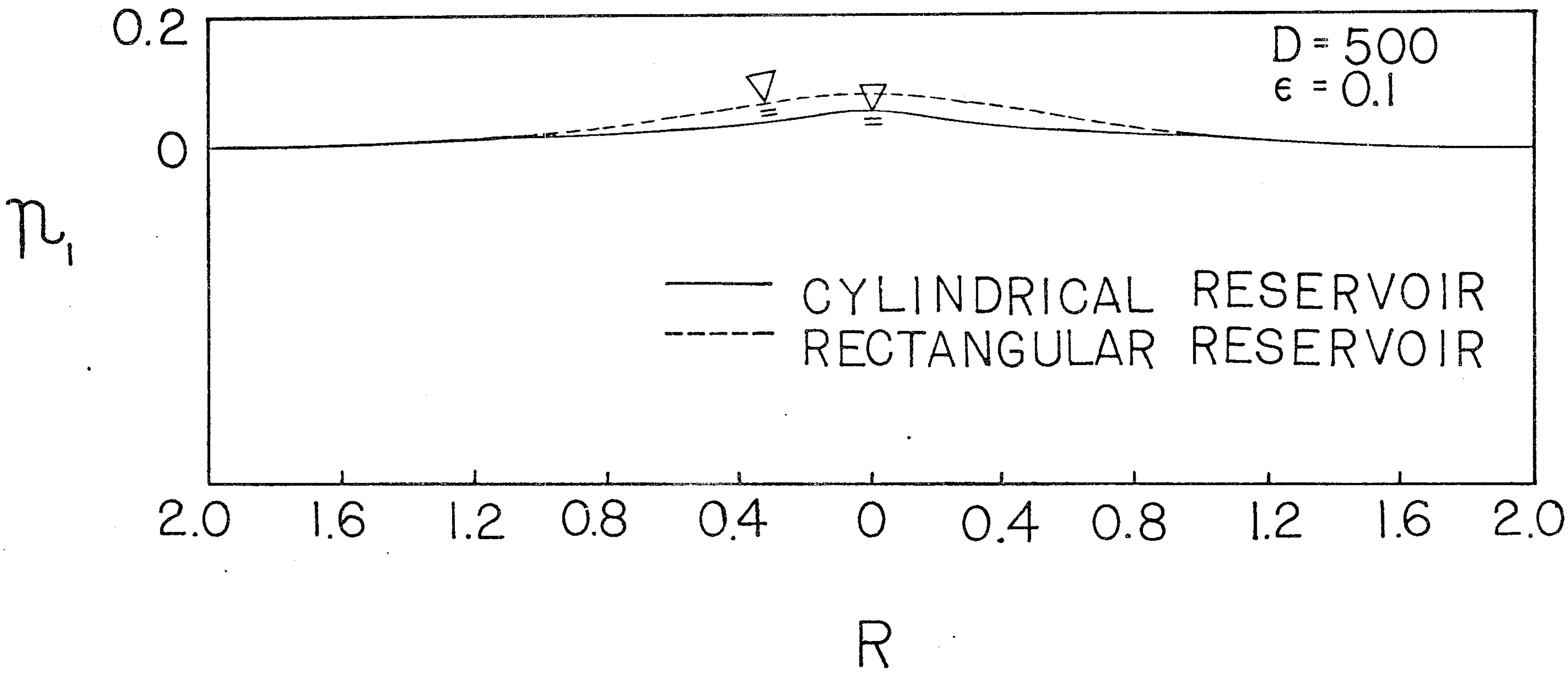


FIG. 3.1-13 EFFECT OF CONFIGURATION OF RESERVOIR ON THE FIRST-ORDER PERTURBATION FUNCTION FOR THE UPWELLING OF WATER TABLE

## 2. Well Test/Analysis & Physical Modelling

Investigators: B. Chen, L. S. Lau, & P. Takahashi

The research sub-tasks on well test/analysis and physical modelling have defined three areas of focus: hardware evaluation, software evaluation and development, and physical modelling. The following accomplishments can be reported:

1. characterization of the nature of geothermal reservoirs and completion of a survey on geothermal reservoir engineering, including an international questionnaire on the state-of-the-art in geothermal engineering,
2. survey on the availability and relative cost of hardware for geothermal fluid and environment measurement,
3. training program initiated to acquaint task members with the principles of well testing, analysis and performance prediction, with special emphasis placed on hands-on experience,
4. preliminary design of a physical model,
5. coordination with geophysical drilling program established to insure that all necessary analytical parameters are measured.

The following work is in progress:

1. continuance of training program,
2. frequent interchange with geophysics,
3. survey on availability of software for well analysis and performance prediction,
4. detailed analysis into the techniques of well testing,
5. development of a physical model.

A discussion of the work in Phase I is given in Technical Report No. 3, Geothermal Reservoir Engineering: State-of-the-Art. The following is a brief summary of this report; additional details can be found in the report itself.

## 1. The Nature of a Geothermal Reservoir

The "state-of-the-art" in geothermal reservoir engineering is in the most part formative. Three groups in particular, though, have contributed well: New Zealand [1 - 27]*, the U. S. Geological Survey [29 - 40], and Stanford University [41 - 47]. Also available are some individual investigations, as for example, Test Well Mesa [28] and Whiting's reservoir engineering study of Wairakei [48].

The primary reason why the literature is relatively sparse is that private companies treat geothermal well testing, the data, and methods of analysis as proprietary. Certain legal restrictions furthermore tend to preserve this form of classification.

Speculations on the nature of geothermal reservoirs can be found in the literature. Geothermal reservoirs can be characterized in several ways:

A. Depletable (self-sealed) or regenerative (recharged),

B. Physical state,

1) vapor - steam,

2) liquid - hot-water, normally two-phased at wellhead,

3) solid - hot rock,

4) liquid magma.

C. Physical condition,

1) temperature/pressure,

2) size/depth,

3) production.

D. Degree of dissolved solid content.

In California, vapor dominated wells are considered to be depletable. A tax allowance is allowed under this classification. A decision has not yet been made on other types of wells. There is some reason to believe that all wells are at least partially regenerative because of the meteoric

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* References are listed on pp.154 to 157.

(rainwater) origin of geothermal fluids [49]. Furthermore, reports of measurable pressure drops in steam-dominated geothermal fields seen after rainfall lead one to suspect that perhaps fluid recharge could be significant.

Although vapor-dominated geothermal wells are generally contaminated with $CO_2$ (primarily) and $H_2S$, there is little dissolved solid content. On the other hand, some of the hot water well samples in the Imperial Valley have shown as much as 30% dissolved solids by weight.

There seems to be no clear cut answer to a universal definition of a geothermal reservoir. A geothermal reservoir needs:

A. A heat source, magma or geopressure,

B. To be confined in an aquifer, although non-permeable hot rocks can be transformed into an aquifer through hydrofracturing/thermal cracking and the addition of water,

C. Caprock--to hold the hot fluid in place.

Speculations of how a geothermal reservoir might look have been advanced by White and Muffler [49, 50], U.S.; Facca [51], Italy; Elder [52], New Zealand; and Hayashida [53], Japan.

Although it has been reported that hot water reservoirs are twenty times more prevalent than vapor-dominated ones [56], technical difficulties in the former have resulted in considerably more production from the latter. Table 3.1-1 shows that five vapor, eleven hot water, and two binary cycle plants are either operating or close to completion [57]. Hot rock concepts are undergoing investigation by researchers from Battelle (for Montana) and the Los Alamos Scientific Laboratory (for New Mexico) [58]. Finally, a fourth concept, direct utilization of magma, was originally advanced by George Kennedy and David Griggs in 1960 [59]. A recent conference on volcano energy (Hilo, Hawaii) supported the reasonability of this latter scheme. Some preliminary work, mostly in the proposal stage, is being

TABLE 3.1-1 GEOTHERMAL PLANTS

| DRY STEAM PLANTS | MW CAPACITY | INITIAL OPERATIONS |
|---|---|---|
| Italy | | |
| Lardarello | 365 | 1904 |
| Monte Amiata | 25 | 1967 |
| U.S.A. | | |
| Geysers, California | 411 | 1960 |
| Japan | | |
| Matsukawa | 20 | 1966 |
| Hachimantai | 10 | 1975 |

| FLASHED STEAM PLANTS | MW CAPACITY | INITIAL OPERATIONS |
|---|---|---|
| New Zealand | | |
| Wairakei | 192 | 1958 |
| Kawerau | 10 | 1969 |
| Japan | | |
| Otake | 13 | 1967 |
| Hatchobaru | 50 | late 1970's |
| Mexico | | |
| Pathe | 3.5 | 1958 |
| Cerro Prieto | 75 | 1973 |
| Iceland | | |
| Namafjall | 3 | 1969 |
| Hengrill | 13-32 | late 1970's |
| Philippines | | |
| Tiwi | 10 | 1969 |
| USSR | | |
| Pauzhetsk | 6 | 1967 |
| El Salvador | | |
| Ahuachapan Field | 30 | 1975 |

| BINARY CYCLE PLANTS | MW CAPACITY | INITIAL OPERATIONS |
|---|---|---|
| USSR | | |
| Paratunka | 1 | 1967 |
| U.S.A. | | |
| Imperial Valley, California | 10-50 | 1975-1980 |

advanced by researchers from Sandia (New Mexico), Lawrence Livermore Laboratory, and the University of Hawaii.

When calculating the usable energy in a geothermal reservoir, one should be aware that only 1% of the total energy is converted to electrical energy from a hot-water reservoir using present proven technology, and from 2% to 5% of a vapor-dominated reservoir can be converted to electricity [49]. It should nevertheless be realized that on an absolute energy scale, a liquid dominated reservoir, per cubic foot of reservoir, contains more energy than a vapor dominated one. Secondly, the thermal conductivity of rock precludes conduction as a mechanism for regenerating a geothermal well. For example, H. Ramey has reported that the net heat recharge rate in the Big Geysers is only 0.6% [60]. However, the possibility of extraordinary fluid convection through porous media as driven by circulating magma should not be discounted--thermal cracking of the cooled magma can result in high permeability.

The general nature of a geothermal reservoir seems to be fairly well understood. There is some contention on the self-sealed/regenerative issue. However, the "state-of-the-art" in a qualitative sense is sufficiently developed--quantitatively, though, the challenges are only now beginning to surface.

## 2. International Questionnaire on the State-of-the-art in Geothermal Reservoir Engineering

An international survey was initiated to determine the "state of the art" in geothermal reservoir engineering. Not only was valuable information obtained from the survey, but it is hoped that the effort will spark development of geothermal reservoir engineering in a spirit of intra/international cooperation.

Over twenty replies were received from companies, institutions, and government agencies in various countries which have geothermal energy production. While some of the responses were received through oral communication, the majority of them were in the form of personal correspondence. Many of the individuals chose to answer the questions by citing published technical literature. The significant responses are tabulated in matrix form in Table 3.1-2.

3. Preliminary Investigation into Geothermal Measurement Hardware and Technique

A) Measurement and Method of Analysis

The purpose of well testing and analysis is to collect enough information to reveal the nature of the reservoir and to determine the pertinent physical parameters which control the behavior of fluids in the reservoir. Some of the questions that need to be asked are:

1) What are the temperature and pressure ranges of the fluid in question?

2) What is the nature of the fluid; i.e., vapor, liquid or a mixture of both?

3) What is the chemical composition of the fluid?

4) What production rate can be maintained and what is the expected life of the reservoir?

After the drill site has been selected, a reservoir analysis and formation evaluation program should be outlined as follows:

1) Bore Hole Tests

(a) Geographical Logging

(b) Driller's Log

(c) Drilling Fluid and Cutting Analysis

(d) Coring and Core Analysis

(e) Drill-stem Tests

(f) Geochemistry Analysis

TABLE 3.1-2 RESPONSES TO INTERNATIONAL QUESTIONNAIRE

| NAME AND AFFILIATION | WHAT IS THE NATURE OF A GEOTHERMAL RESERVOIR | WELL TESTING AND ANALYSIS | |
|---|---|---|---|
| | | HARDWARE | SOFTWARE |
| B. C. McCabe<br>Magma Power Company<br>USA | In geothermal reservoir engineering, the theoretical information to determine the size or longevity of a geothermal field is a very inexact science. For steam and hot water reservoirs, no one knows what the % of replaceable heat is coming into the reservoir in proportion to the amount being withdrawn. Probably, the replacement heat is much greater than it is generally imagined. | No reply | No reply |
| W. K. Summers<br>New Mexico Bureau of Mines<br>USA | Geothermal fluids consist of two components: 1) meteoric water and 2) gases ($H_2S$ and $CO_2$), rising from great depths. The mixture of the components occur in fractures. If the fractures are sufficiently close together, a well will produce routinely. Otherwise, only occasional wells will produce. | Petroleum or groundwater hydrology equipment can be used, as modified to incorporate temperature. | Computer technology is generally adequate, but software is dependent on adequate sampling of the flow continuum and the proper incorporation of the parameter temperature. |
| Giancarlo E. Facca<br>Registered geologist<br>Italy and USA | Geothermal fields are composed of: 1) a deep sequence of layers, heated by an underlying magmatic stock and which, in turn, heats the overlying porous strata, and 2) a very permeable layer with thickness, porosity and permeability of such an order as to allow the formation and the permanence of a system of convection currents in the water filling the pores of the rock, and 3) an impermeable layer over the reservoir. | Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A17, A22, A23). | Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A23, A26, A27, A28). |

TABLE 3.1-2 (CONTINUED)

| | | | |
|---|---|---|---|
| W. E. Allen<br>Oil and Gas Conservation Commission (Arizona)<br>USA | Refer to articles in Appendices A and B. | Refer to articles in Appendices A and B. | For the purpose of predicting well performance, there are no marketing companies in Arizona. |
| Robin Kingston<br>Kingston, Reynolds, Thom, and Allardice, Ltd., New Zealand | Refer to United Nations publications in Appendix A. | Refer to articles by D.K. Wainwright (A11) and A.M. Hunt (A12) in Appendix A. | Prediction of well performance is a composition of permeability, temperature, reservoir capacity, and rate of flow. Permeability in geothermal terms depends on fracture zones much more than on porosity. Oil reservoir assessment techniques can in some applica tions be modified for geothermal applications. |
| Enrico Barbier<br>International Institute for Geothermal Research<br>Italy | Refer to United Nations and UNESCO publications Appendix B (B16, B24). | Equipment and other hardware are generally not avaialble. | The evaluation of the quality of a geothermal well is uncertain. Analogies are generally made with existing wells. |
| J. L. Guiza<br>Geothermal Resources<br>Cerro Prieto<br>Mexico | Geothermal fields are classified into two major groups: 1) sedimentary fields and 2) volcanic fields. In a sedimentary field the productive strata is a permeable sandstone interbedded by impermeable clay layers. The sandstone is saturated with meteoric water, and the heat flow is due to the faults and fissures of the granitic basement. In volcanic fields the possible production mechanism is due to the water flow through fissures in the volcanic rocks being heated by a cooling magmatic body. | For the determination of reservoir parameters such as permeability index and porosity, the synergetic log named SARABAND is used. For temperature, pressure, and flow measurements the conventional systems (Kuster RPG and KTG instruments) are employed. | The performance in a well can be predicted by means of a hydrologic model modified by the temperature effect and taking into account the physical characteristics of the productive sandstone as well as the physical-chemical properties of the geothermal fluids. For the purpose of optimizing well locations, computer programs are used to simulate field production. |

2) Well Completion Methods

3) Well Tests

   (a) Temperature Survey

   (b) Pressure Survey

   (c) Pressure Drawdown Test

   (d) Pressure Buildup Test

   (e) Flowrate and Enthalpy Measurements

   (f) Geochemistry Analysis

   (g) Well Interference Test

4) <u>Reservoir Analysis and Formation Evaluation Interpretation</u>

   The petroleum industry has developed most of the above testing instruments and procedures. However, one cannot blindly use their methods to interpret the results of the tests to geothermal fields. A geothermal reservoir in general has a higher temperature than a petroleum reservoir. Furthermore, most of the petroleum reservoir analysis is based on isothermal conditions which do not hold in a geothermal field. Whiting [61] and Ramey [60] have successfully demonstrated that the regular volumetric balance method in petroleum engineering does not apply to geothermal reservoir but rather a material and energy balance method is needed.

In the general sense, software encompasses both computer programs and the standard type curve analysis. It appears that the methods of well analysis used in the petroleum and gas industries cannot be naively applied to geothermal systems.

The general analytical solutions for transient flow in petroleum reservoirs have been obtained for three different types of boundary conditions:

(a) infinite reservoir, line source well,

(b) bounded circular reservoir,

(c) constant pressure outer boundary.

The actual solutions have been presented many times in the petroleum literature; e.g., Matthews & Russel, <u>Pressure Buildup and Flow Tests in Wells</u>.

The basic assumptions in obtaining these solutions can be summarized as follows:

(a) Temperature is constant throughout the reservoir,

(b) Fluids have small and constant compressibilities.

The solutions are generally presented by plotting pressure versus temperature on log-log type paper.

Horner [62], in his 1951 classic paper, developed a way to graph the pressure buildup test data versus time on semi-log paper. From this, one can calculate permeability, skin effect, flow efficiency, and static average pressure. However, a great deal of difficulty has been encountered when one tries to apply the theory to a specific problem. Horner's method requires one to estimate on the semi-log graph paper a straight line (i.e., the quasi-steady state condition). This can be extremely difficult since the onset of the straight line can be seconds, minutes, hours, days, or even weeks. One can never be sure that the straight line chosen is the right one.

Fortunately, this deficiency can be remedied by plotting the data against a log-log type curve. Ramey [63] has demonstrated that this method permits one to determine easily whether one's data are truly on the semi-log straight line.

The above analysis works very well for oil and gas wells subjected to the two assumptions stated before. One has to be careful when one applies these methods to a geothermal reservoir situation or incorrect results will be obtained.

First, depending upon the reservoir condition and production rate, a geothermal reservoir may or may not be isothermal. If non-isothermal conditions prevail, then the above analysis needs modification in order to be useful.

Secondly, there is a good possibility that the fluid flow in the reservoir may be two-phased. One has to develop the appropriate curve to take this effect into account.

Finally, in general one cannot completely shut in a geothermal well; therefore, a multirate flow test technique has to be used.

Well test analysis, though, can perhaps best be summarized by quoting Alex Muraszew, writing on "Geothermal Resources and the Environment," in the 1972 GEOTHERMAL WORLD DIRECTORY [64],

> "....with the present state-of-the-art, neither the capacity of the reservoir nor its longevity can be accurately predicted...."

Fortunately, as undeveloped as this field is, definite progress is being shown. The Stanford Group has made admirable progress. A parallel laboratory study extending the work of Miller [65] and Cady [66] is being pursued at Stanford. The U.S.G.S. is devoting effort towards computer model studies with M. Nathanson, of the Menlo Park unit, beginning to publish. The University of Hawaii group is adding to this body of knowledge. The geo/hydrology group at California-Berkeley, has produced excellent computer models in this area.

In summary, the types of ongoing software analytical work include:

1) Prediction of performance and resources available from temperature and pressure data.

2) Reservoir simulation.

3) Well log analysis.

B) <u>Hardware</u>

Well tests are performed in two phases. In the first phase, tests are performed during open hole drilling operations. They consist of fluid temperature measurement, fluid sampling, core analysis, and formation logging. After completion, the producing well must undergo a second phase of tests to determine the thermodynamic condition of the fluid and the adequacy of the reservoir producing zone. Measurements are taken both at the wellhead and downhole. The two well-test phases are:

1) <u>Open hole tests</u>

While the drilling operation is in progress the drilling fluid is continuously monitored for signs of increasing temperature gradient. The drill cuttings are also observed for indications of possible zones of fluid production. If temperatures begin to rise sharply with a corresponding increase in rock porosity, the drilling is stopped to perform a formation log. Simply described, in formation logging, a probe is lowered into a well at the end of a multiconductor cable and the physical parameters are measured and recorded as functions of depth to obtain well logs.

The three common forms of formation logs are electrical, sonic, and radioactive.

2) <u>Producing well tests</u>

After completion, the producing well must undergo a second phase of tests. The downhole tests consist of measuring fluid parameters such as temperature, pressure, and flow rate. See Figure 3.1-14. Although there are many ways of performing the tests, the two common methods are wireline operations and combination tool logging.

In wireline operations a measuring probe is lowered into a well at the end of a stainless steel cable. The surface equipment consists of depth measuring devices, weight indicators, line-speed indicators, and a motorized take up reel. The probe is made of a steel tubing with the recording and measuring instruments located internally. The recorder is attached to the end of the interchangeable measuring instruments as shown in Figure 3.1-14. The deflection of the stylus makes a mark on a black recording chart. After the probe is extracted from the well, the marks on the chart are read with a chart reader. Conversions to the desired parameter are made with a calibration table for each type of fluid measuring device.

Like most other logging instruments, the combination tool is lowered into a well at the end of a multiconductor cable. The fluid parameters are measured and, in turn, recorded automatically on the surface recorder equipment. The combination tool is ideally suited for a production well since the production flow profile has a relatively high rate as compared to a well in its exploratory stage.

While numerous types of tests may be performed in a production well, both the buildup and pressure drawdown tests

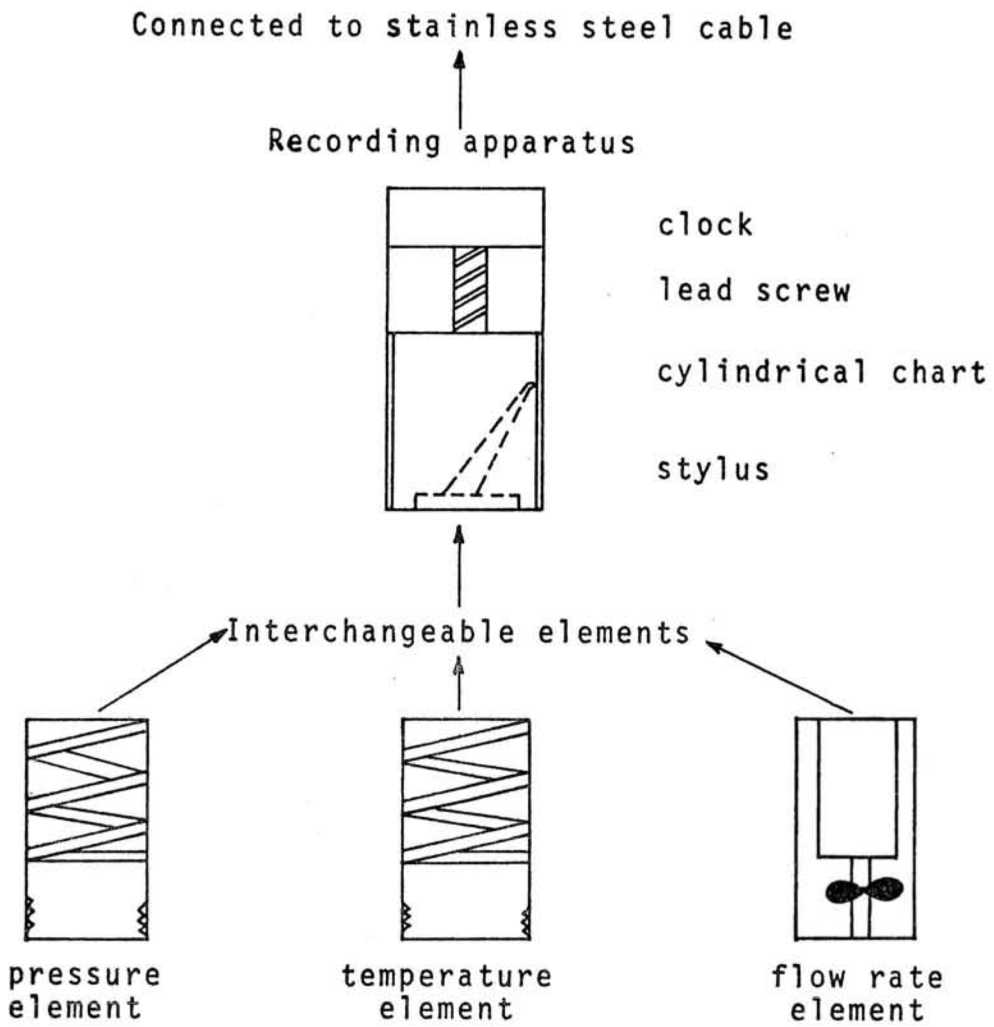


FIG. 3.1-14 SCHEMATIC DIAGRAM OF WIRELINE INSTRUMENTS

are of prime interest. The pressure behavior of a well is readily measurable and is a very useful property. Both types of tests are valuable tools for obtaining information about reservoir properties.

The theory of pressure buildup assumes a well is closed in, and that after it is closed in, no production enters the wellbore. Information such as the transmissivity (the product of the average permeability and the thickness of the reservoir), skin effects and flow efficiency can be estimated to aid the prediction of future production rate and production life of the reservoir. A pressure drawdown test consists of a series of pressure measurements made during a period of flow at a constant rate. An extended drawdown test should be run to estimate reservoir volume.

Correspondence has been initiated with various well test service companies and institutions. With the exceptions of Schlumberger and Kuster Company, most of the firms have had little experience in testing geothermal wells. The proprietary nature of the results has somewhat constrained information gathering. However, replies have indicated that Schlumberger and Kuster have the expertise to perform the task. Specifically, the logging methods are well developed by Schlumberger, and the Kuster Company has various types of wireline instruments for geothermal fluid measurement. With this fact in mind a preliminary commitment can be made to select the type of hardware for the two testing phases.

Since the initial testing phase consists of formation and packer tool logging, the services will probably be contracted out to a firm such as Schlumberger Well Service Company. The log interpreting computer program named SARABAND was developed by this firm, and it has been used successfully at Cerro Prieto and at Imperial Valley. The program interprets the log data and determines automatically the desired downhole parameters, and its use should be very helpful for the Hawaii Geothermal Project.

In the second testing phase the Kuster instruments will probably be used for the purpose of reservoir analysis. The cost of the instruments is about one tenth of the combination logging tool, and their reliability and sensitivity (0.4 psig for pressure and 0.3°F for temperature) are ideal for newly explored geothermal wells.

4) Preliminary analysis into the physical modelling of a geothermal reservoir

The physical model is a necessary balance to the ongoing software investigations. The physical model will not only serve as a convenient check on the computer model, but will simulate conditions not easily attempted by software. The objectives of the initial physical model studies will be to bring together known information about related laboratory studies, analyze the state-of-the-art, design the hardware system required for simulation, initiate fabrication, and conduct preliminary parametric tests.

Very little physical modelling work has been reported in the literature. The significant studies related to geothermal reservoirs include those of G. Cady [66], H. Henry and F. Kahout [67], and the remotely related work of J. Bear [68]. However, none of the reported investigations approached the problem on a total systems basis while considering the high temperatures expected.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. This force is created by heat within the geothermal system which decreases the fluid density.

The dimensionless number determined to be of prime interest to the study is the Rayleigh Number ($N_{Ra}$). The Rayleigh Number is the product of the Grashof ($N_{Gr}$) and Prandtl ($N_{Pr}$) Numbers, where

$$N_{Gr} = \frac{\text{buoyant force}}{\text{viscous force}} \quad \ldots \ldots \ldots \ldots \quad (1)$$

$$N_{Pr} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \quad \ldots \ldots \ldots \ldots \quad (2)$$

$$N_{Ra} = N_{Gr} \cdot N_{Pr} = \frac{\rho_s g \beta K (T - T_s) h}{\mu \alpha} \quad \ldots \ldots \ldots \quad (3)$$

where $\rho_s$ = density of fluid, (4)

$g$ = gravitational constant, (5)

$\beta$ = coefficient of thermal expansion, (6)

$K$ = permeability of porous medium, (7)

$(T-T_s)$ = temperature driving force, (8)

$h$ = depth of permeable bed, (9)

$\mu$ = viscosity of fluid, (10)

$\alpha$ = thermal diffusivity of fluid (11)

The literature is sparse on the range of Rayleigh Numbers meaningful to actual geothermal systems. In general the study will investigate the range of $N_{Ra}$ between 30 and 1000. This will be accomplished by altering the permeability of the solid medium and the temperature of the system. The permeability can be altered by changing the mesh size of the sand or glass bead bed. The temperature change will in turn determine the values of the coefficient of thermal expansion ($\beta$), thermal diffusivity ($\alpha$), viscosity ($\mu$), and density ($\rho$) of the fluid.

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## TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

Investigators: H. C. Chai, J. Chou & D. Kihara

### 1. Heat Balances

The design of a power plant is dictated by economic justification in a competitive society. Economic designs can be achieved only by careful analysis of all the possible solutions for a given situation. Such analysis is usually started from heat balances of various plant schemes to establish the respective heat rates and equipment sizes. Heat balances have been made to evaluate the effects of superheating geothermal steam by auxiliary fuel and using deep ocean water as cooling water in a condenser.

The presence of moisture in steam could reduce the turbine efficiency and cause the erosion of turbine blading. By superheating the low-pressure geothermal steam, it is possible to have dry exhaust steam. It was found that the heat rates of auxiliary fuel for superheating are comparable to the heat rates of modern central power plants.

For a geothermal plant near the sea, the cost of using sea water as cooling water in a condenser is likely to be lower than the cost of recycling the cooling water through a cooling tower. The average temperature of sea water is about 80°F at the surface and 40°F at a depth of 1,600 ft. Since the enthalpy drop per unit temperature at the low-pressure end of a steam turbine is much larger than that at the high-pressure end, the gain in power output by using deep-ocean water for cooling was found impressive.

### 2. Optimal Operating Pressures of Vapor Flashing Plant

In a vapor flashing system, hot water is flashed to vapor in cyclone separators at pressures lower than wellhead pressure. The vapors thus generated are used to drive a mixed-pressure turbine. The lower the flashing pressure, the higher the production rate of vapor. However, available energy associated with each pound of steam decreases with lowering of the separator pressure. A maximum power output exists for a certain combination of the operating pressures of separators. A numerical method has been worked out to optimize the operating pressures with consideration of different degrees of flashing efficiency and heat losses. In general, the temperatures which correspond to the vapor pressures in separators should be about equally distributed as suggested by Hansen [1]; for example, the optimum operating temperatures of a three-stage flashing plant are 330°F, 260°F and 190°F if the saturated temperature of input brine is 400°F and the exhaust from the turbine condenses at 120°F.

The number of flashing stages is a matter of economic justification. Power contribution of an additional stage decreases as the number of stages increases. The total work of a four-stage flashing is only 5% higher than that of a three-stage flashing for the saturated well water at 400°F and the turbine exhaust at 120°F.

3. Flow Rate of Hot Water Wells

The parameters which affect the production from a liquid-dominated aquifer are pressure and temperature of reservoir, depth of well, drawdown pressure, wellhead pressure, diameter of well and surface friction. The interrelationship among these parameters has been studied with a simplified procedure for the calculations, which will be improved shortly. The projected results should be helpful to the interpretation of well testing data and to the selection of the operating pressure of a self-flowing well.

Problems of pumping hot brine from a well have also been considered. It appears there is no commercial equipment available for forcing the hot brine out from a very deep well, although some pump manufacturers showed an unusual degree of interest in the development of submersible pumps to handle hot brines.

4. Regenerative Binary Cycle

The word binary is used because two fluids are involved in the power production process, the geothermal fluid and the working fluid. There is an increasing interest in the utilization of heat from hot brine at 250°F to 450°F by using a fluid, such as Freon or isobutane, as the working fluid to operate in a closed Rankine cycle. To improve the basic cycle, such as that shown in Fig. 3.6-1, addition of a regenerative heat exchanger is proposed. Its function is to interchange the energy between the superheated exhaust from turbine and the condensate to be returned to the boiler. This study has shown that a regenerative isobutane cycle can significantly reduce the heat rejection from the plant and may lower the cost of power produced. Furthermore, the discharge temperature of brine in a regenerative cycle is much higher than that in a basic cycle; thus the waste heat can be used for producing fresh water with a multiple-effect evaporator as illustrated in the flow diagram of Fig. 3.6-2, which shows that nearly one half of the hot brine can be converted into fresh water. For geothermal reservoirs located in areas where the supply of fresh water is inadequate, the combination of a regenerative isobutane power plant with a multiple-effect evaporator could be a sound solution to the compounded problems of power and water.

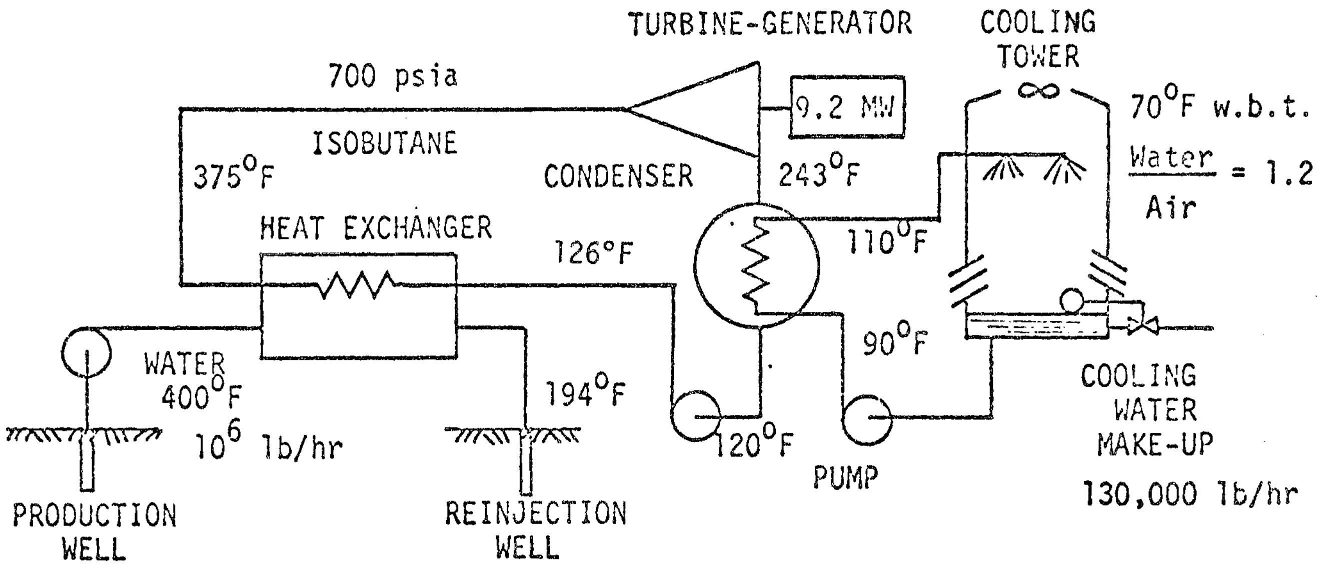


FIG. 3.6-1 BASIC ISOBUTANE CYCLE

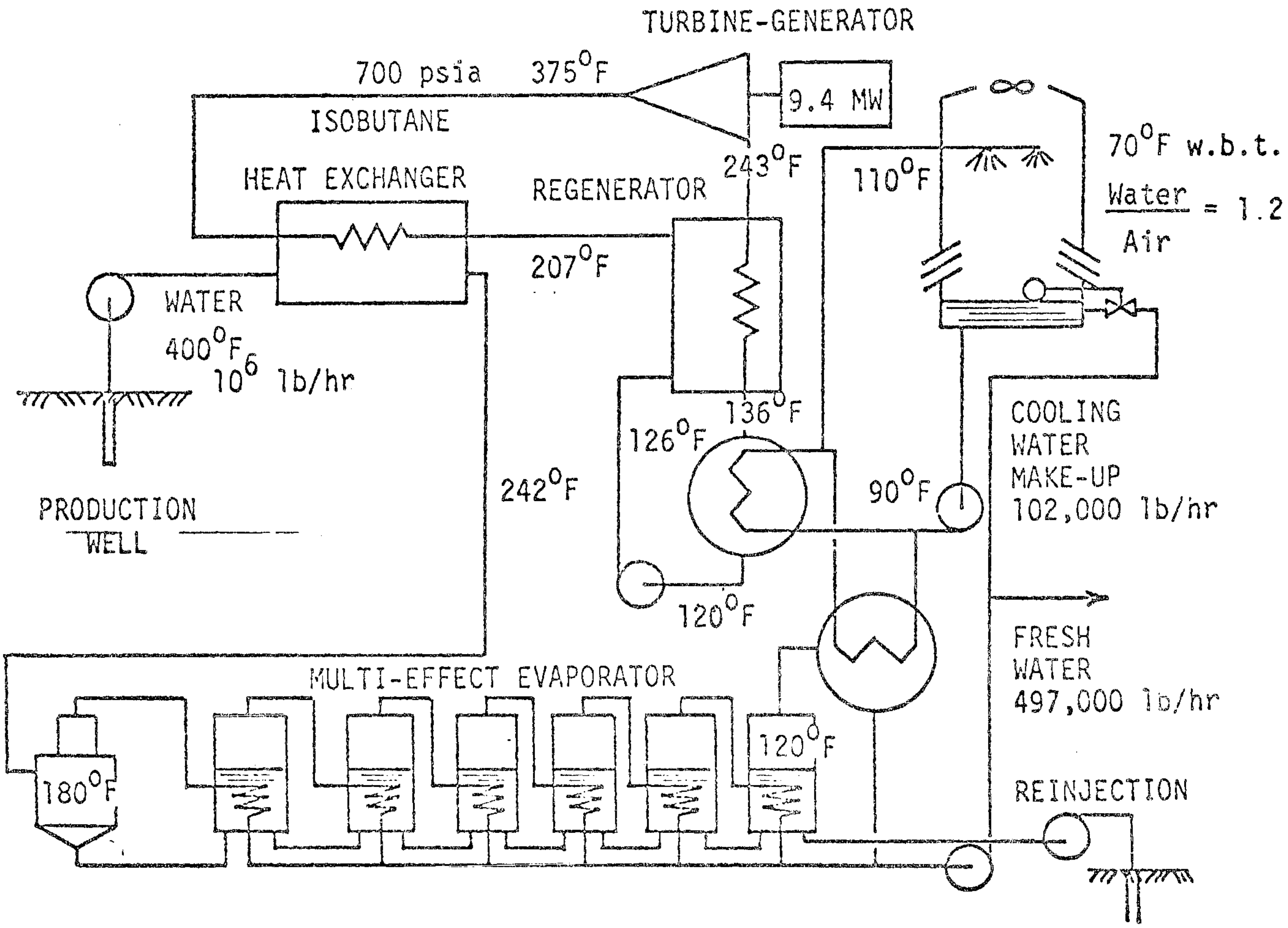


FIG. 3.6-2 REGENERATIVE VAPOR-TURBINE CYCLE AND MULTI-EFFECT EVAPORATOR

In a liquid-dominated field, the geothermal fluid may be delivered from a well by flashing or by pumping. With a self-flowing well by flashing, the geothermal fluid appears in two phases at the wellhead, and the working fluid in a binary system should be heated in two stages. It is first heated by the geothermal liquid, then by the flashed vapor. As a case study, calculations have been made to determine the power outputs of a basic binary cycle and a regenerative binary cycle with two-phase water from the well under the following assumptions:

| | |
|---|---|
| Rate of flow. . . . . . . . . . . . . . . . . . . . | $10^6$ $lb_m$/hr, |
| Temperature of water. . . . . . . . . . . . . . . . | 400°F, |
| Composition of water by weight. . . . . . . . . . . | 20% vapor and 80% liquid, |
| Turbine efficiency. . . . . . . . . . . . . . . . . | 85%, |
| Feed pump efficiency. . . . . . . . . . . . . . . . | 80%, |
| Minimum temperature difference in heat exchangers. . . . . . . . . . . . . . . . . . | 10°F, |
| Condensing temperature. . . . . . . . . . . . . . . | 120°F. |
| Working fluid . . . . . . . . . . . . . . . . . . . | isobutane |

At every throttle pressure, there is an optimum throttle temperature to yield the maximum power output. The results of calculations are tabulated in Tables 3.6-1 and 3.6-2. The highest power output in this case is at 700 psia throttle pressure. There is a significant increase in power output by using regenerative heat exchangers. The capital cost of a regenerator could be partly offset by the reduction of the size of the main heat exchanger. Since the heat rejection equipment is

TABLE 3.6-1 PERFORMANCES OF BASIC ISOBUTANE CYCLE

| WORKING PRESSURE psia | OPTIMUM THROTTLE TEMP., °F | ISOBUTANE FLOW RATE $10^6 lb_m/hr$ | POWER OUTPUT MW | HEAT REJECTION $10^6$ BTU/hr | WATER LEAVING TEMP., °F |
|---|---|---|---|---|---|
| 500 | 380 | 1.810 | 16.33 | 381.22 | 135 |
| 600 | 390 | 1.901 | 17.70 | 376.49 | 135 |
| 700 | 375 | 1.948 | 19.535 | 369.12 | 136 |
| 800 | 375 | 2.028 | 18.398 | 371.09 | 138 |
| 900 | 375 | 2.065 | 18.443 | 369.93 | 139 |

For $10^6$ $lb_m$/hr of two-phase water (20% vapor, 80% liquid) at 400°F, 120°F condensing temperature.

TABLE 3.6-2 PERFORMANCES OF REGENERATIVE ISOBUTANE CYCLE

| WORKING PRESSURE psia | OPTIMUM THROTTLE TEMP., $^oF$ | ISOBUTANE FLOW RATE $10^6$ $lb_m$/he | POWER OUTPUT MW | HEAT REJECTION $10^6$ BTU/hr | WATER LEAVING TEMP., $^oF$ |
|---|---|---|---|---|---|
| 500 | 380 | 1.996 | 18.013 | 264.87 | 245 |
| 600 | 390 | 2.076 | 19.33 | 275.52 | 230 |
| 700 | 375 | 2.101 | 21.07 | 283.01 | 217 |
| 800 | 375 | 2.183 | 19.819 | 294.02 | 210 |
| 900 | 380 | 2.223 | 19.862 | 303.94 | 200 |

For $10^6$ $lb_m$/hr of two-phase water (20% vapor, 80% liquid) at 400$^o$F, 120$^o$F condensing temperature.

a major cost item of geothermal power plants, the cost of regenerative cycle plants should be lower than the cost of basic cycle plants of the same capacity.

5. <u>Heat Exchanger Design</u>

Since one objective of a geothermal power plant is to maximize the power output for a given well production rate, initial efforts were concentrated on one of the factors limiting the conversion of thermal energy to electrical energy, i.e., the transfer of heat from the hot brine to the working fluid. However, many of the parameters that govern the performance of the heat exchange equipment are also parameters that affect the characteristics of the Rankine cycle, e.g., pressure, temperature, velocity of working fluid. Because of the interdependence of heat exchange characteristics and cycle performance, computer programs for these two areas were interfaced and run in tandem.

The computer programs modelling the system under consideration have the following characteristics:

A. Rankine Cycle Computer Program

1. Input
    a. Table of property values of working fluid
    b. Turbine inlet conditions; pressure and temperature
    c. Condenser outlet conditions; pressure and temperature
    d. Component efficiencies
    e. Required power output

2. Output
    a. Property values of working fluid at all points in the cycle
    b. Cycle efficiency
    c. Mass flow rate of working fluid for required power output
    d. Heat rejection rate

B. Boiler and Superheater Computer Program

1. Input
   a. Properties of brine and working fluid
   b. Brine inlet temperature and velocity
   c. Working fluid inlet temperature and pressure
   d. Pinch point temperature difference
   e. Tube material, diameter, spacing
   f. Fouling factors

2. Output
   a. Convective heat transfer coefficients on both sides
   b. Number and length of tubes required
   c. Total heat transfer rate across tube walls
   d. Ratio of mass flow rates - brine to working fluid

To observe general trends in the heat exchanger specifications, the preliminary design of a vertical counterflow heat exchanger was completed for a system having the following nominal conditions:

Heat source . . . . . . . . . . . . . . Water at 350°F

Working fluid . . . . . . . . . . . . . Isobutane (R-600a)

Pinch point temperature difference . . . 20°F

Velocity of working fluid . . . . . . . 7 ft/sec.

Condenser outlet. . . . . . . . . . . . Saturated liquid at 100°F

Turbine efficiency. . . . . . . . . . . 85%

Pump efficiency . . . . . . . . . . . . 75%

Net power output. . . . . . . . . . . . 10MW

Pressure losses, heat losses, and fouling neglected

The hot brine is assumed to be circulating inside the tubes because of cleaning considerations. In the non-boiling section, the equation recommended by Kays [2] was used. In the boiling region, the correlation equation by Chen [3] was used.

In Figure 3.6-3, the minimum tube length required as a function of turbine inlet temperature is roughly 150 feet. The total number of tubes required is shown in Figure 3.6-4. For comparison purposes, the

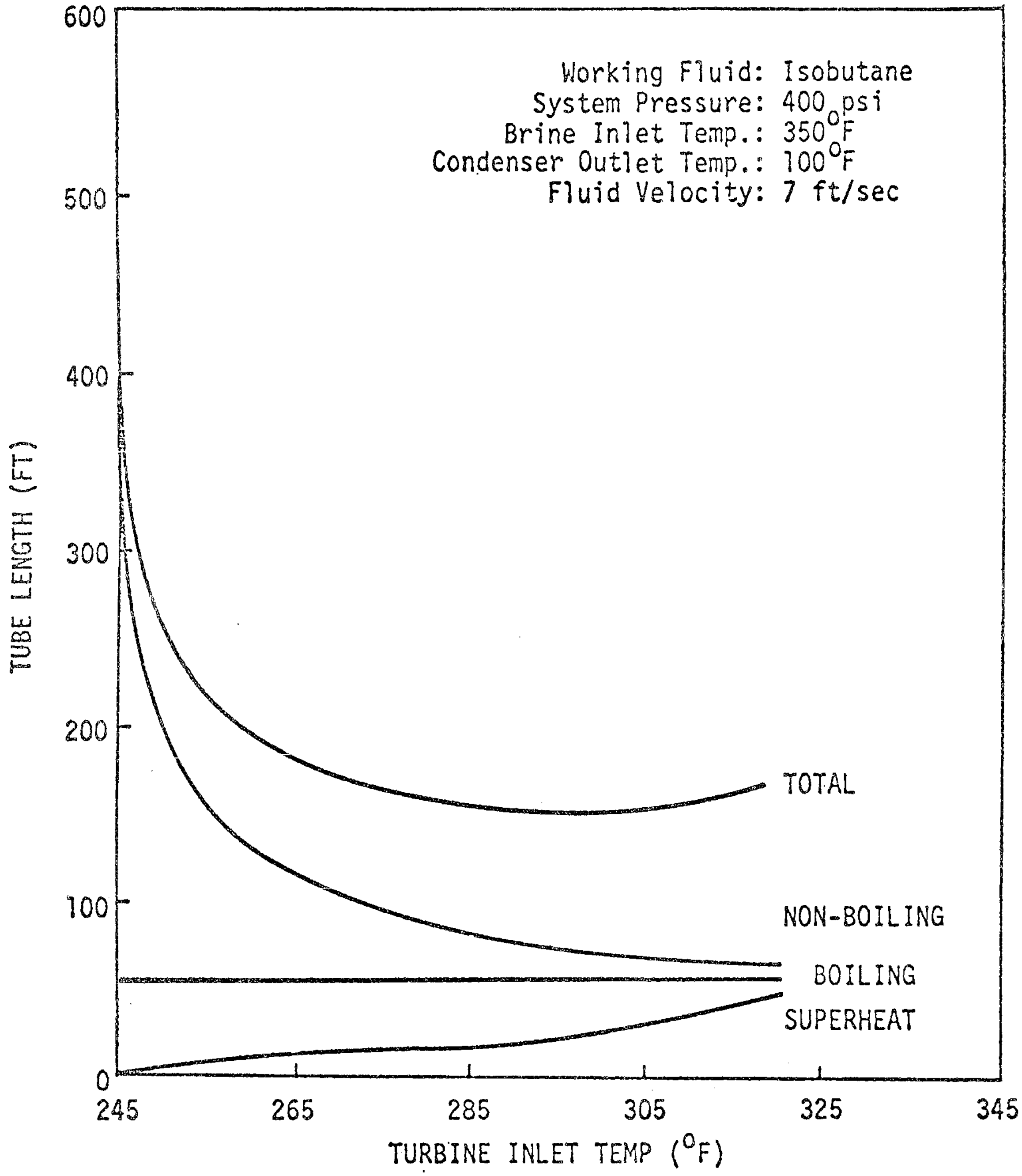


FIG. 3.6-3 TUBE LENGTHS AS A FUNCTION OF TURBINE INLET TEMPERATURE

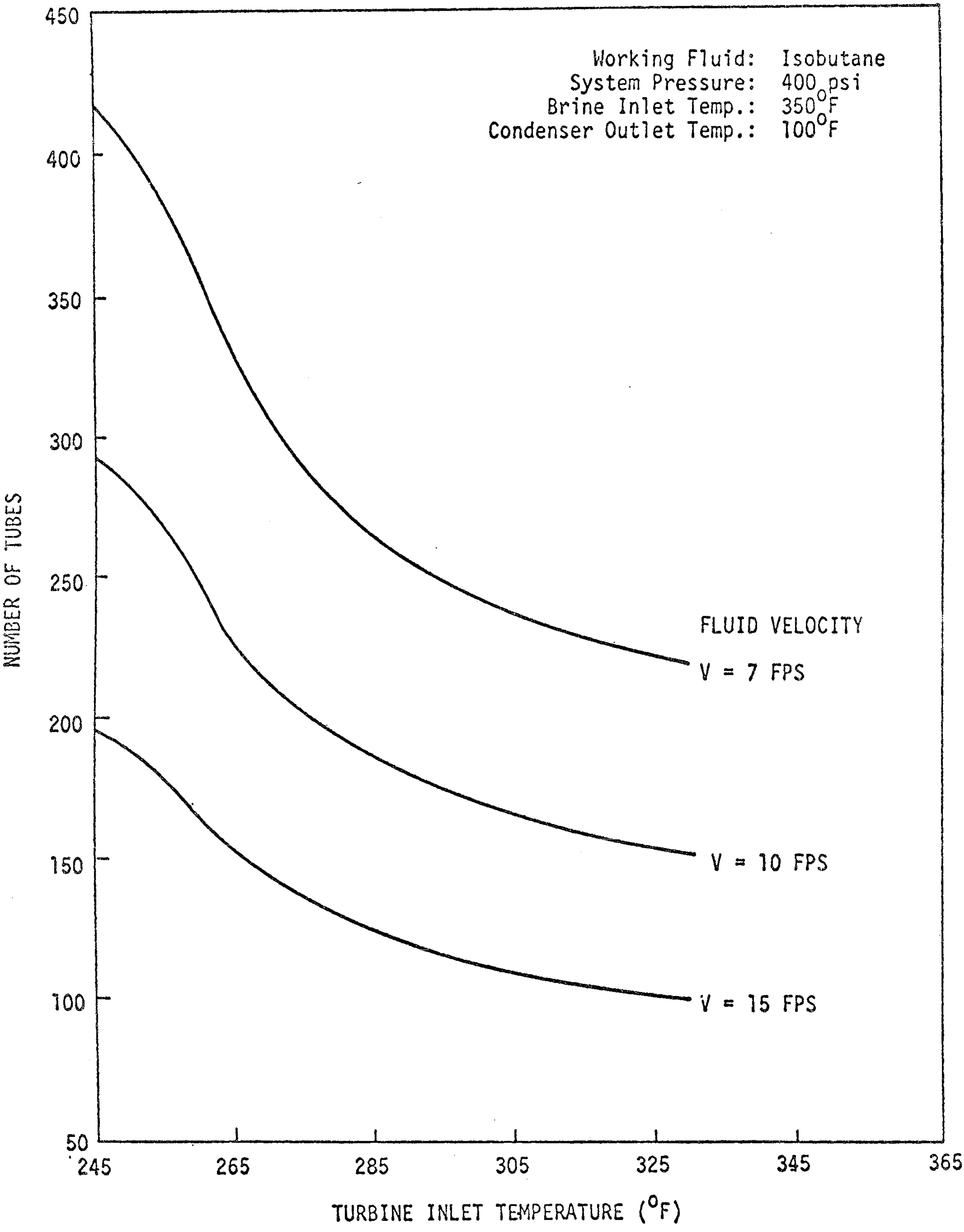


FIG. 3.6-4 NUMBER OF TUBES AS A FUNCTION OF TURBINE INLET TEMPERATURE

number of tubes required for other values of fluid velocity is also indicated. Figure 3.6-5 shows the pressure drop across the heat exchanger. It is interesting to note that a minimum value occurs at a turbine inlet temperature of approximately 300°F.

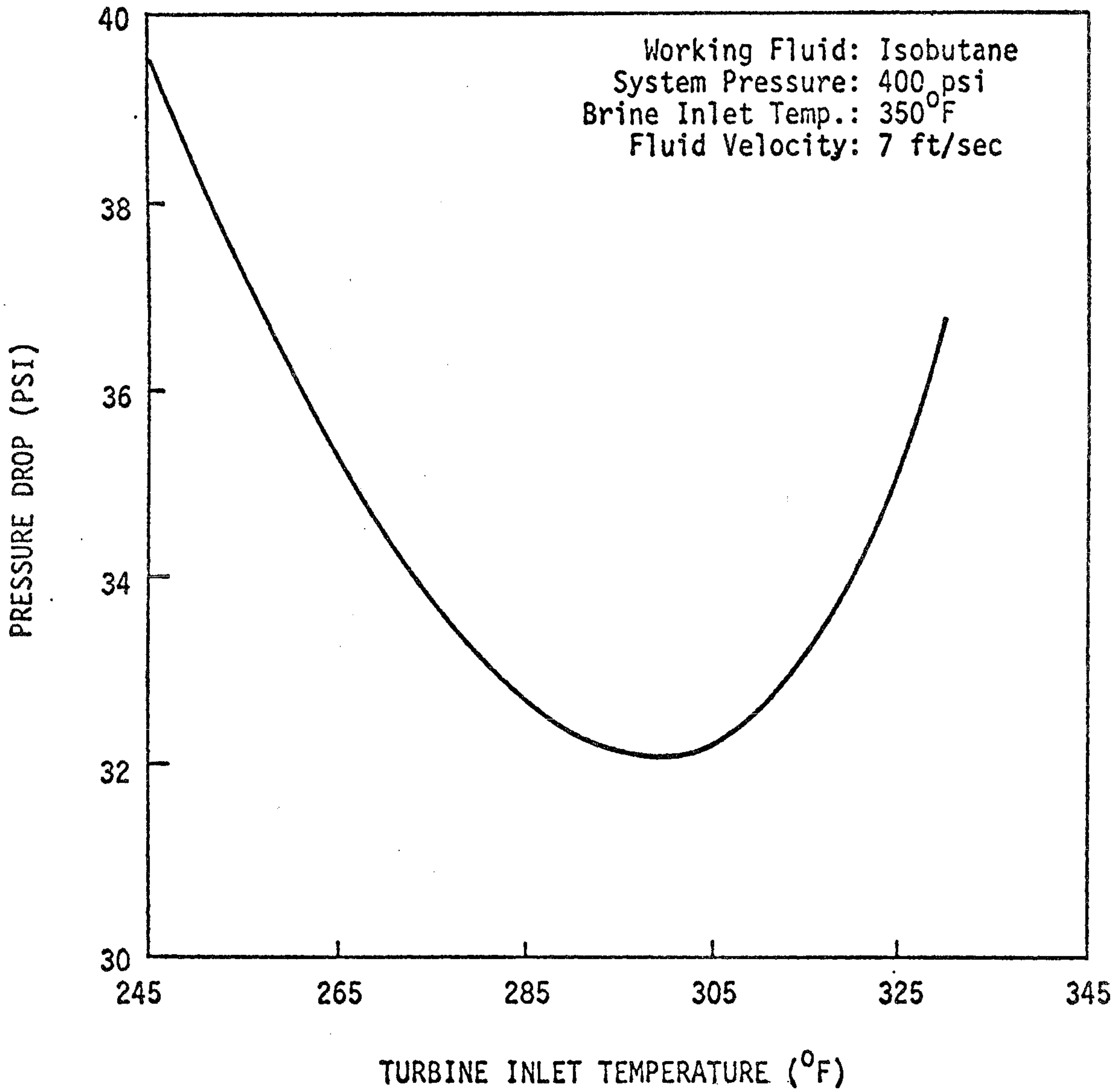


FIG. 3.6-5 HEAT EXCHANGER PRESSURE DROP FOR FLUID VELOCITY OF 7 FT/SEC

HAWAII GEOTHERMAL PROJECT

Environmental-Socioeconomic Program

Principal Investigator:
Robert M. Kamins

INTRODUCTION

Two basic interests underlie this portion of the Hawaii Geothermal Project. One is to ascertain the impact of geothermal power production on the economy and social order of the State, particularly on land use, economic growth and diversification, cost of living, employment, population growth and its spatial distribution. The analysis takes into account changes in legislation, public utility regulation and development planning necessitated by this new source of energy in Hawaii; it considers how applicable the experience of this state would be to other areas of the U.S., including its Pacific territories.

The second interest is to determine how to minimize possible adverse effects of geothermal development on the environment and local ecosystems. This interest is interlinked with the first, since Hawaii's economy is already heavily dependent on tourism and aspires to attract more scientific research centers, and both these activities are enhanced by protection of the natural environment.

The 1973-74 national energy shortage is being felt with special force by Hawaii, which has not developed in significant quantity any energy sources alternative to oil.* Consequently, public and governmental interest in geothermal energy has deepened considerably since this project began in May 1973. It is now looked to as a possible means of reducing the state's virtually complete dependence on oil imports and as a potential source of new jobs in a presently

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*On a few of the Hawaiian Islands small hydroelectric plants and steam obtained by burning bagasse at sugar mills provide marginal sources of energy for the local electric companies.

stagnant local economy. (The level of unemployment in the State of Hawaii rose to an average of 7% in the first quarter of 1974 and remained there into June.) One of the uses of the research conducted under this program is to set reasonable limits to these expectations, assuming that geothermal resources of commercial value are discovered.

## Program by Major Tasks

### Task 4.0: Program Support

Support services and coordination will be provided for the four line tasks involving 12 faculty members, four students and two consultants who will be participating in the Socioeconomic-Environmental Program. Communication with the appropriate State of Hawaii and County of Hawaii officials concerned with the legal, regulatory, planning and environmental aspects of geothermal development will continue to be maintained.

### Task 4.1: Environmental Aspects

The key event affecting the timing of this task is the drilling of holes for geothermal exploration. Of particular concern is drilling that will penetrate through the Ghyben-Herzberg lens. Both the "intermediate" holes averaging 2,000 feet in depth and the "deep" holes which will be approximately 6,000 feet deep fall into this category. It is presently estimated that the drilling of the "intermediate" holes will begin during the summer of 1975. The "deep" holes are scheduled for commencement of drilling during the spring of 1976.

Baseline studies on the chemical, physical and biological characteristics of the lens will be evaluated through tests conducted on the "shallow" wells that will penetrate to the lens. It is possible that constituents of the underlying water such as salinity, entrained gases and heat may degrade the lens through vertical mixing within the shaft and lateral diffusion into the porous volcanic rock substrate. Baseline data on the lens obtained through studies on the "shallow" wells in conjunction with careful monitoring to detect any changes in the lens during the drilling of "intermediate" and "deep" wells are thus essential. Drilling sites that are considered vulnerable to significantly adverse effects on the Ghyben-Herzberg lens will be avoided. It is anticipated that the drilling will have a minimal impact on the surface environment. However, the laying of roads necessary for mobilization of the drilling rig and related equipment might have a significant impact. Therefore, baseline studies will be required prior to any road construction. These baseline studies will include the characterization of flora and fauna and the identification of any significant archeological sites within the three proposed drilling areas, with greatest emphasis on possible road corridors and potential "deep" well sites. The archeological investigation will be made by a specialist in pre-Cook Hawaiian history in consultation with the Bishop Museum. Unique Hawaiian ecosystems, rare and endangered species and important archeological sites will be avoided. Other sites of significant but lesser ecological or archeological importance will be avoided if possible; economic considerations, notably potential for geothermal energy and access will have to be given full consideration.

Results of these baseline studies will also provide information for preparation of environmental impact statements, if required, for proposed road construction and "intermediate" and "deep" well drilling.

A further use of the aforementioned studies will be to assess the potential environmental impact of the construction and operation of energy generating facilities, assuming one or more of the "deep" test holes provide the necessary geothermal source. Additional environmental baseline studies dealing with air quality and meterological conditions will also be required for this purpose. Gases, such as $H_2S$ and ammonia that might be entrained in the geothermal energy source, may be liberated in significant amounts into the atmosphere upon being brought to the surface. If so, they will be studied to assess the impact of gas liberation on local ambient air quality and of any possible deleterious effects on flora and fauna. If cooling towers are required, the meterological investigations will also provide essential data on the possible impact of the towers on local weather.

If it appears that deep ocean water may be used as a coolant for geothermal power production, the baseline studies will be extended to this portion of the environment, examining the ocean at the sites indicated by the geological and engineering tasks to be likely sites for cold water intake and warm water discharge.

The baseline studies will be conducted under the direction of the Environmental Center of the University of Hawaii.

Task 4.2: <u>Legal and Regulatory Aspects</u>

During the last half of 1973, researchers in this task invited to informal discussions at the University representatives of the State and County agencies most directly concerned with geothermal development -- the Department of Land and Natural Resources, the Office of the Attorney General, the Department of Planning and Economic Development and the Department of Regulatory Agencies, all of the state, and the Department of Research and Development of the County of Hawaii. From these meetings there was developed a bill to establish a legal regime for geothermal resources in Hawaii, that is, to define geothermal resources and determine their ownership. The bill was redrafted by the Department of Land and Natural Resources and introduced as part of the administration's legislative program.

The report summarized the status of federal and state law bearing on geothermal deposits and discussed water law cases in Hawaii which may be pertinent. It took no position with respect to private or public ownership of the subsurface resource, but did indicate that until the issue of ownership was resolved the uncertainty would inhibit utilization of any geothermal fields which may be discovered.

The 1974 Hawaii Legislature subsequently passed a bill (HB 2197-74) to establish a legal regime for geothermal resources in Hawaii, for legal purposes defining them as a mineral and by that definition reserving them as property of the State government. The law, signed by the Governor in June 1974, is brief and leaves detailed regulation of geothermal production to the State Department of Land and Natural Resources.

A preliminary draft of possible regulatory provisions has been prepared for the project by David N. Anderson, Geothermal Officer of the State of California. The draft will be worked over with the Hawaii Department of Land and Natural Resources, which has administrative responsibility for all "mineral" resources of the state, but no experience with geothermal energy. It is anticipated that some of this work, plus possible clarifying amendments to the new geothermal statute, will continue through the first quarter of 1975, when the State Legislature meets in regular session.

In mid-1975, assuming that initial indications from test drilling are not strongly negative, the task will be extended to working with the State Department of Regulatory Agencies concerning the rules and procedures of public utility regulation which would be applicable to geothermal steam production and distribution. If negative test results or other factors lead the Department to the conclusion that it was premature to consider how it would regulate the economics of geothermal steam operation, then this portion of the task would be deferred.

Task. 4.3: Land-Use and Planning Aspects

After potential sites for drilling geothermal wells are identified, this task will identify the owners of the sites -- whether public agency or private holders -- and help negotiate with the owners or managers of the land for permission to drill.

Over the entire sequence of geothermal exploration, drilling and production, the project will work with appropriate State and County agencies concerning the possible impact of geothermal development on land use in the vicinity of the wells. Consultation with both levels of government will be necessary to ensure that there are no barriers to development imposed by land-use laws. As geothermal resources are identified, the State Planning and Economic Development and the Hawaii County Department of Research and Development will be informed, so that the development plans of both levels of government can be modified to take these new resources into account. Liaison with the State Department of Land and Natural Resources, the designated administrator of state-owned geothermal resources, will be maintained.

Task 4.4: Economics

During Phase I of the Hawaii Geothermal Project we prepared an annotated bibliography on Geothermal Power Economics, with more than 200 items. Utilizing this bibliography, we began to compile an inventory of geothermal production units around the world, emphasizing production and cost data. This data will be used to set some of the parameters for modelling economic impact projections for geothermal development on the Island and within the State of Hawaii. To this same purpose, the best estimates of the costs of alternative energy sources for Hawaii -- oil, nuclear power and solar energy -- are being gathered.

A study of energy use on the Island and in the State of Hawaii, projected to approximately 1990, has been begun and will be completed by the end of 1975. It will estimate the potential impact of geothermal power production -- at several assumed levels of megawatt capacity -- on the Hawaii economy. The study will cover the following: import substitution effects (i.e. the results of substituting geothermal power for oil in the production of electricity); industrial growth effects (the potential for new, energy-intensive industries plus the stimulation of existing industries); by-product utilization; employment effects; population dispersion effects; public revenue effects.

In this study, input-output and econometric models of Hawaii County and Hawaii State will be utilized as seems most feasible after completion of the examination of existing models, to be conducted in the last half of 1974. Also projected is a section on investment decision-making in geothermal resource development, adopting a Bayesian feasibility model initially applied to the field of petroleum exploration.

The study will also address the strategy of economic development on the base of geothermal resources, considering the respective roles of public and private investment. The specialness of the Hawaii case, and the elements of its economy more or less common to other areas of the United States, will both be noted so that the transferability of this analysis can be seen.

As the technology of utilizing geothermal resources as they may occur in

Hawaii is worked out, the Economics program will furnish consultation on economic aspects of well location to the drilling program and on the economic aspects of plant design to the Engineering program.

# HAWAII GEOTHERMAL PROJECT

Preliminary Proposal for Research Deep Hole Exploratory Drilling

Principal Investigator:
Agatin T. Abbott

## INTRODUCTION

As the various avenues of research and exploration which have been described earlier in this report are being completed or are in various stages of completion, it becomes clear that the next logical step in the search for geothermal energy on the island of Hawaii is to test beneath the surface by drilling.

At this time three areas on the island of Hawaii have been selected as being the most promising. These are the East Rift of Kilauea (Puna Rift), the Southwest Rift of Kilauea, and the Southwest Rift of Mauna Loa. According to the present plan exploratory drilling will be undertaken in those areas in the order in which they are mentioned above.

## PREVIOUS WORK

The drilling program is based on the results of a number of other lines of investigation and research that have been carried out during earlier stages of the Hawaii Geothermal Project. Reference is made to tasks under Phase I Geophysics, Tasks 2.1 Photogeologic; 2.2, 2.4 Electromagnetic; 2.3 Electrical Resistivity; 2.5 Microseismic. Reference is also made under Phase I Extension Geophysics, Tasks 2.1 Preparation for Exploratory Drilling, 2.2 Geoelectric, 2.3 Gravity and Magnetic, 2.4 Thermal, 2.5 Microseismic, 2.6 Geochemical. Under Engineering Task 3.1 Reservoir Engineering, and under Environmental-Socioeconomic, Tasks 4.3, 4, 5 Legal and Planning. Most of the preparatory effort has been concentrated in the Puna area. The other two areas are being studied this summer.

A large amount of information is contained in earlier works on the geology and groundwater hydrology of portions of the island of Hawaii, that was not done for the express purpose of gaining geothermal information. These references are provided at the end of this chapter.

PERSONNEL

Because the exploratory and research drilling program of the Hawaii Geothermal Project is very large, both in terms of financial involvement and also in terms of the fields of interest that it encompasses, the personnel to manage this phase is as follows:

Co-principal Investigator and Director of Exploratory Drilling -

Agatin T. Abbott, Geology and Management
University of Hawaii

Site Selection and Operations Committee

Agatin T. Abbott - Geology, Univ. of Hawaii
Pow-Foong Fan - Geochemistry, Univ. of Hawaii
Augustine S. Furumoto - Geophysics, Univ. of Hawaii
Gordon A. Macdonald - Geology, Univ. of Hawaii
Donald Peterson - Geology, U.S. Geol. Survey
Charles Zablocki - Geophysics, U.S. Geol. Survey

The role of the Site Selection and Operations Committee is a decision making one regarding all phases of the drilling program and integration of the drilling program with other phases of the HGP such as Geophysics, Engineering, and Legal and Socio-economics. There must be a close association between the several fields of interest in this project, if the maximum benefit is to be achieved from the holes drilled.

In order to have as large an input as possible from knowledgeable persons who are in one way or another concerned with geothermal energy, a large body of advisors has been invited to contribute ideas and suggestions as the project continues. There will undoubtedly be additional names added as time goes along, but at the present time the following persons comprise the Advisory Group:

David Anderson - State of California Resources

Kenneth Brunot - National Science Foundation (formerly Phillips Petro. Co.)

Dan Davis - U.S.G.S.

Robert Kamins - University of Hawaii

Douglas Klein - University of Hawaii

George Keller - Colorado School of Mines

George Kennedy - University of California, L. A.

Kost Pankiwskyj - University of Hawaii

Henry Ramey - Stanford University

Robert Rex - Republic Geothermal Company

Fred Smales - Hawaiian Cement Company

Harold Stearns - U.S.G.S., retired

Robert Tilling - U.S.G.S.

John Unger - U.S.G.S.

Donald White - U.S.G.S.

George Woollard - Hawaii Institute of Geophysics

Paul Yuen - University of Hawaii

## DRILLING MANAGEMENT

It is the opinion of the Site Selection and Operations Committee that the most effective and in the long run the least costly system of managing the drilling operations is to employ a professional engineering firm and delegate to it the responsibility of handling contracts, sub-contracts, bids, drilling procedures, down hole measurements, safety regulations, leases, clean-up specifications and a host of related arrangements that can much better be managed by a professional firm than by the personnel of the Hawaii Geothermal Project.

The decisions on such matters as location of the holes, number of holes, types of scientific measurements to be made, coring procedures depth or termination of a hole and similar matters relating to the gathering of scientific and technical data and the assessment of their results will rest with the Site Selection and Operations Committee.

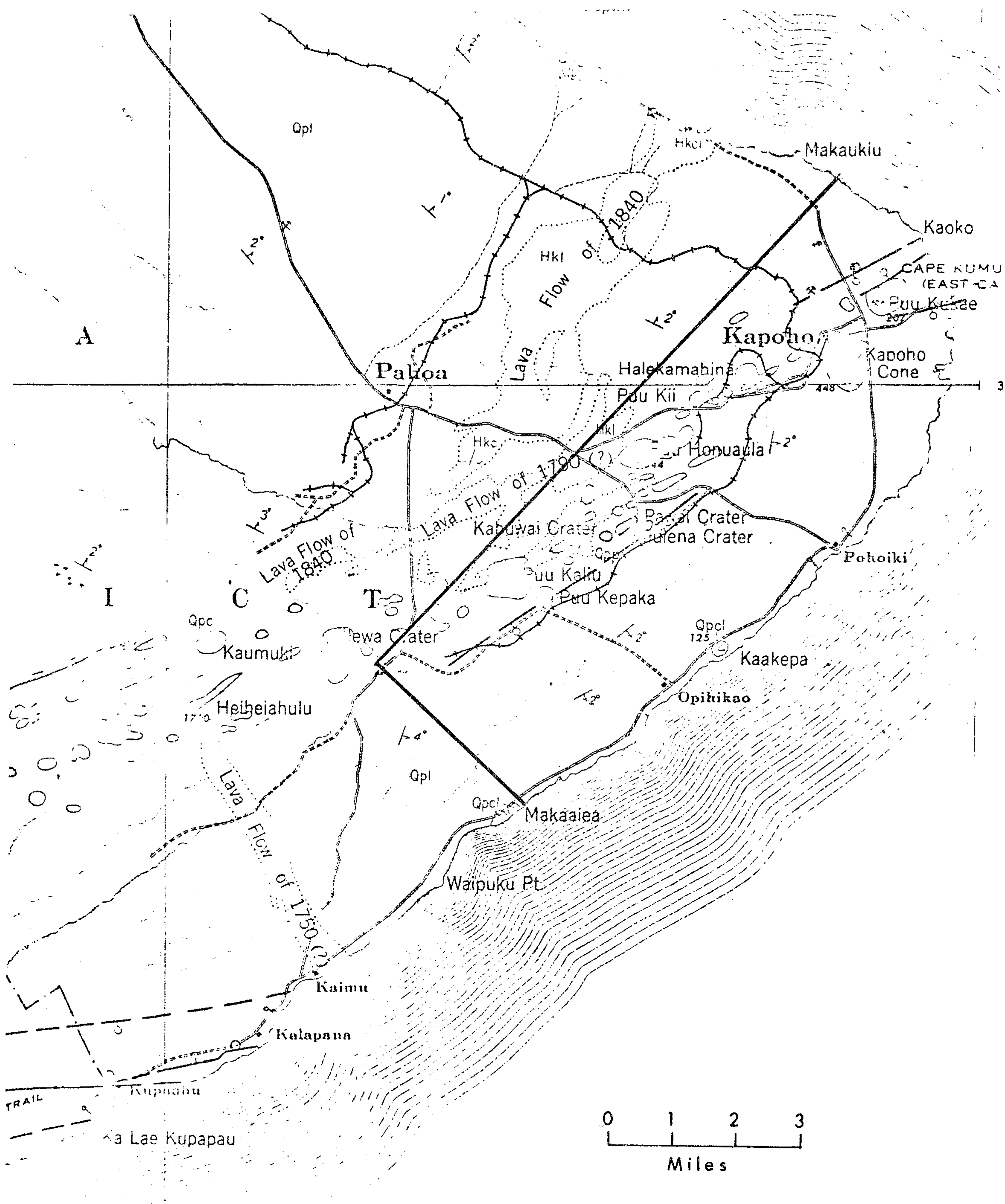
It will be the responsibility of the Site Selection and Operations Committee to choose the engineering firm that will assume the job of Program Management for the drilling.

PLAN FOR EXPLORATORY RESEARCH DRILLING

1. East Rift of Kilauea

At the present time of planning the drilling program encompasses three types of holes: (1) shallow holes (average depth - 500 feet) for water samples and temperature measurements. (2) intermediate depth holes (2000 feet) for temperature measurements, rock alternation, water chemistry. (3) deep hole (6,000 feet or more) to try to reach a potential geothermal source and for deep hole data.

The rationale on the drilling of exploratory holes to 6,000 feet or deeper is that if there exists volcanic heat at those depths the hydrostatic




Approximate Boundary of Area Considered for Exploratory Research Drilling in Puna District, Island of Hawaii. (map after Stearns & Macdonald, 1945) pressure of the overlying ocean water at depths of 6,000 feet or more water temperatures could reach over 400°F in the peripheral areas of a volcanic heat source. Under a hydrostatic head of 6,000 feet there would be no surface manifestation of the submerged hot water zone. It is this type of environment that the deep drilling is attempting to discover.

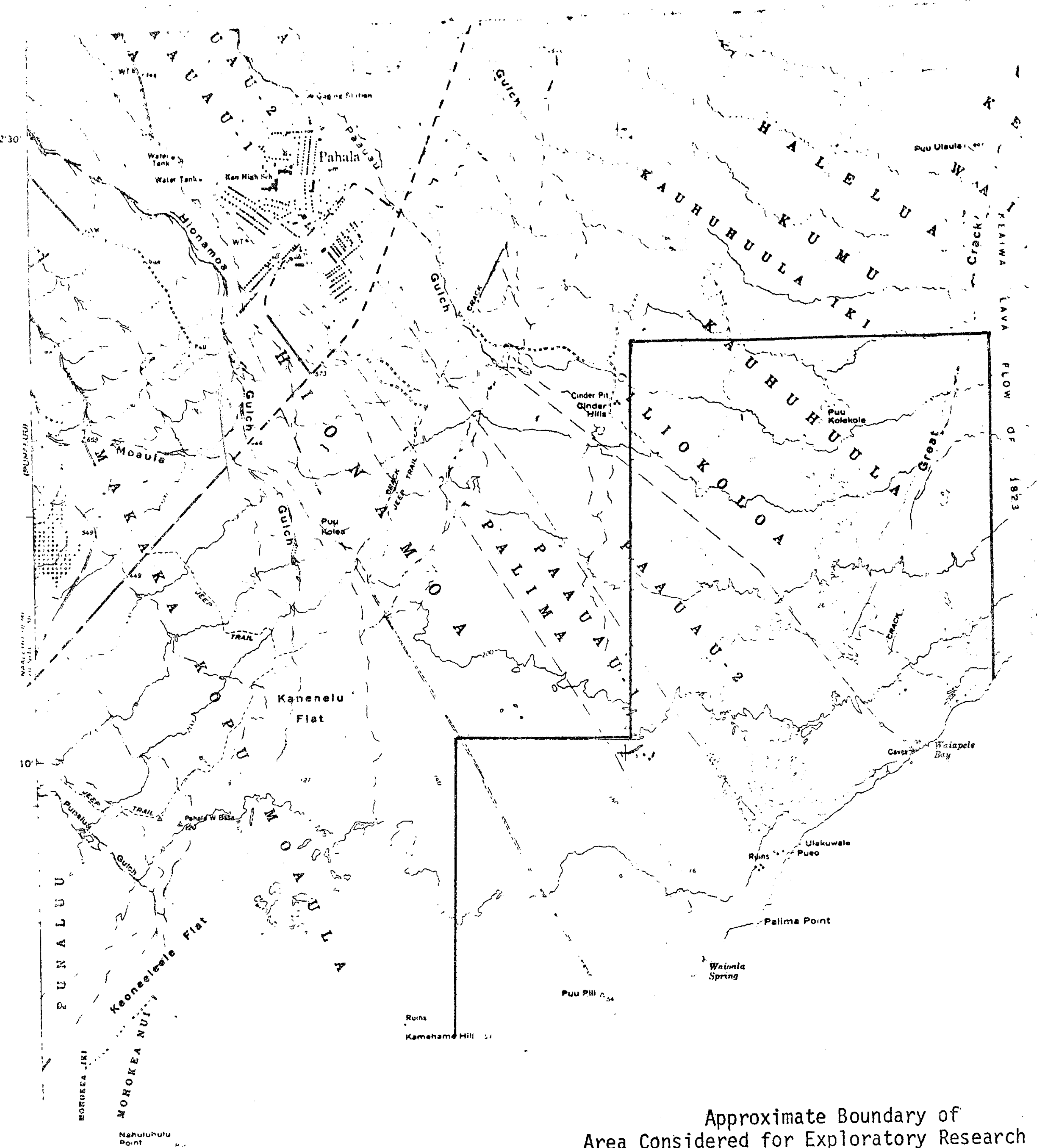
The East Rift of Kilauea is perhaps the best known of the three areas under consideration. It contains a number of drilled wells, and is the scene of considerable activity by real estate sub-dividers. It has been studied intensely over the years by scientists of many disciplines.

Measurement of water temperatures and water chemistry has been completed in most of the accessible wells in the Puna District (See report by Dr. Pow-Foong Fan). The geophysical data is included in earlier reports for the HGP. Self potential survey is presently underway (see report by Dr. Charles Zablocki).

No specific sites for drill holes are shown in this proposal because the field data are still incomplete. When as much data as possible within a reasonable length of time have been assembled (probably the end of the summer), the Site Selection Committee will designate sites for the proposed drill holes. The shallow hole locations will be decided first, and then depending on the information gathered from them plus all other information the intermediate depth holes will be spotted. Depending then on the results obtained in the intermediate holes, the decision regarding the location of the principal hole to a depth of 6,000 feet or more will be made.

2. Southwest Rift of Kilauea

The Southwest Rift of Kilauea is not really so well known from the standpoint of geology, geophysics, or groundwater hydrology as the East Rift. It is an uninhabited lower portion of the Kaʻu desert and contains few roads and one or two trails.




Approximate Boundary of
Area Considered for Exploratory Research
Drilling in Vicinity of Great Crack, Island of Hawaii

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Mile

The principal indication of thermal anomalies at this time are those of the infrared scanning surveys. Geophysical surveys will be conducted in the area during the summer. IR imagery is in part reacting to surface texture.

The same sequence of drilling is planned for this area as for the Puna district, i.e. shallow holes first, followed by intermediate depth holes, and then a deep probe to 6,000 feet or more.

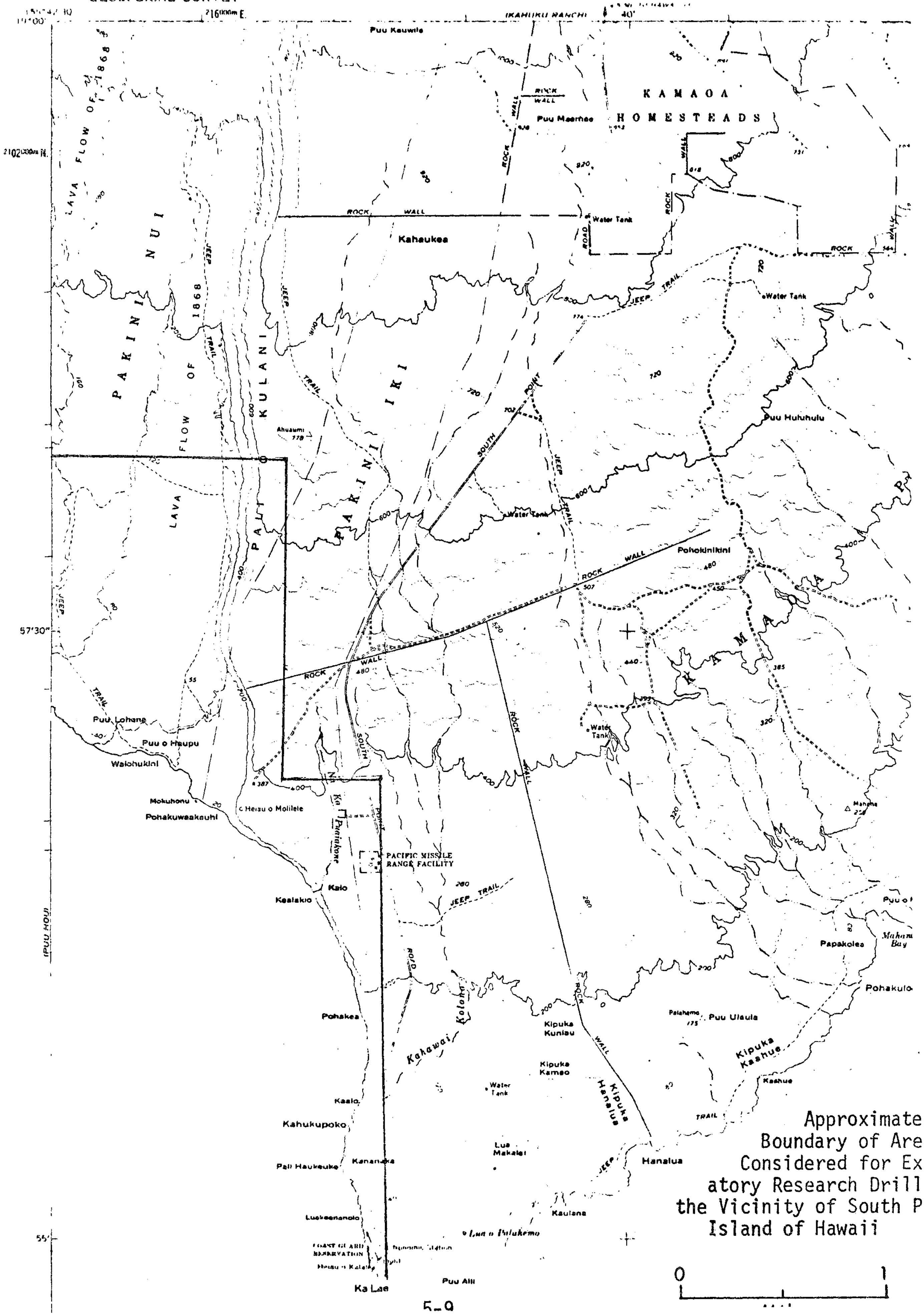
3. Southwest Rift of Mauna Loa

Plans for drilling in the lower portion southwest rift of Mauna Loa are still tentative. Infrared scanning results indicate a possible temperature rise along certain sections of the Kahuku fault scarp. The infrared results may be influenced by cliff steepness or texture of broken rock along the base of the pali. A body of warmer ocean water is also indicated offshore.

On the other hand the Kahuku fault is a major structural feature and probably extends to great depths as well as extending for over 25 miles on the surface and under the ocean. Even though the infrared may be reporting effects other than temperature the Southwest Rift still appears to hold a certain amount of promise as a major structural feature, that could influence heat flow from depth.

No geophysical results are available at this time for the South Point area. Geophysical surveys are planned during the summer of 1974.

DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY




Approximate Boundary of Area Considered for Exploratory Research Drilling in the Vicinity of South Point, Island of Hawaii

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## Geology and Ground-water Hydrology

by Gordon A. Macdonald

### INTRODUCTION

The island of Hawaii is formed by five major volcanoes. Kohala, at the north end, and Mauna Kea, next to the south, have not been active in historic time, and the last eruptions took place several thousand years ago. On the west side of the island, Hualalai erupted last in the years 1800-1801. Since the advent of European and American visitors to Hawaii and the beginning of written records, Mauna Loa and Kilauea have been among the world's most active volcanoes. Mauna Loa erupted last in 1950. Kilauea has erupted repeatedly since 1952, and has been in eruption almost continuously since 1969.

Both Kilauea and Mauna Loa are indented by summit calderas, whose floors are as much as 180 meters below the rims. The calderas were formerly somewhat deeper, but have been partly filled by lava flows. As exposed in the dissected calderas of older volcanoes on other Hawaiian islands, the lavas filling the caldera tend to be considerably denser, more massive, and less permeable than those on the flanks of the volcano outside the caldera. In some of them, such as the Koolau caldera on Oahu and the East Molokai caldera, further reduction in permeability has resulted from alteration of the rocks by gases rising through them, with transformation of pyroxene to chlorite and epidote, and deposition of secondary quartz, calcite, and zeolites in vesicles and other openings. Similar changes can be presumed to have occurred, at least to some extent, beneath the caldera depressions of Kilauea and Mauna Loa.

Extending outward from the calderas are rift zones--zones of innumerable open or filled fissures that have served as pathways for the rise of the magma that produced most of the eruptions. (A few eruptions take place away from the rift zones.) Kilauea and Mauna Loa each have two major rift zones. At the surface the rift zones are marked not only by fissures, but also by many spatter cones and ramparts and cinder cones built at the site of eruptions, and by a few pit craters. Parts of the rift zones are bordered by faults, between which the intervening area has sunk to form a shallow graben. Similar rift zones exposed by erosion on older Hawaiian volcanoes contain thousands of dikes, formed by consolidation of the magma in the fissures. Individual dikes may reach as much as 15 m in thickness, but most of them are less than 5 feet. Transects of the dissected rift zones typically give counts of several hundred dikes per kilometer, and more than 350 per kilometer per mile of width of rift zone is not uncommon. The attitude of the dikes varies considerably, but most of them strike more or less parallel to the rift zone and dip in other direction at angles greater than 70$^{\circ}$.

Between the dikes there remain many slices of basalt lava flows. The inter-dike lava-flow masses consist of both pahoehoe and aa flows, generally thin bedded, and identical to those on the flanks of the volcano away from the rift zones. For the most part they are moderately to highly permeable. The openings primarily responsible for the permeability are joints, inter-flow spaces, openings between the fragments in aa clinker layers, and lava tubes. Vesicles are too poorly interconnected to contribute importantly to the permeability. Alteration and secondary mineralization like that described in the caldera-filling rocks is essentially absent in the dissected rift zones, extending at the most only a few hundred feet beyond the caldera boundary.

Information on the geology and hydrology pertinent to the possible occurrence and entrapment of geothermal resources is given in the following sections for each of the areas thought to be most promising for geothermal exploration.

## East Rift Zone of Kilauea

The east rift zone extends southeastward from Kilauea Caldera for about six kilometers, then bends abruptly east-northeastward and extends through Cape Kumukahi, the eastern point of the island. Beyond the cape it forms a broad east-northeast-trending ridge on the ocean floor for another 65 kilometers (Malahoff and McCoy, 1967). Northwest of the bend the rift zone is marked by a row of pit craters (the Chain of Craters), and a few spatter-and-cinder cones. East-northeast of the bend more than 60 spatter and cinder cones mark the sites of pre-historic, but geologically recent, eruptions along the rift zone. Just before the beginning of written history eruptions took place on the eastern part of the rift zone in about 1750 and 1790. Historic eruptions along it have occurred in 1840, 1922, 1923, 1955, 1960, 1961, 1962, 1963, 1965, 1968, and 1969 to the present.

The area known as East Puna consists of the part of Kilauea Volcano east of about 155$^{o}$ west latitude. It is a broad gently sloping ridge built by lava flows from the east rift zone, and the rift zone extends along its crest. It is situated more or less mid-way between Kilauea caldera and the termination of the rift-zone ridge at the ocean floor. Within it, between the 500-meter contour and sea level, eruptions have occurred in about 1750 and 1790, and in 1840, 1955, and 1960. In 1924, very numerous earthquakes and volcanic tremor accompanied the disappearance of the lava lake in Kilauea caldera and the sinking of the floor of a graben along the rift zone close to sea level in East Puna; although no molten lava appeared at the surface above sea level it is virtually certain that a large volume of magma moved eastward through the rift zone. The surface expression of the rift zone is about three kilometers wide.

East of Cape Kumukahi the submarine cones along the rift zone appear very fresh in photographs. A submarine eruption occurred a few kilometers offshore in 1884.

Lava flows from vents along the rift zone have poured down slope, building a broad structural arch that plunges east-northeastward at an angle of 1 to $2^{o}$. North of the rift zone the lava beds dip 2 or $3^{o}$ northeastward. South of it the dips are 2 to $4^{o}$ southeastward. Locally on the south side of the ridge, dips of more than $6^{o}$ probably are the result of lava flows mantling a southeast-facing fault scarp (Stearns and Macdonald, 1946, plate 1). The lava flows are of both pahoehoe and aa types No specific determinations of permeability are available, but similar lavas yield water freely to wells, and over-all permeability is unquestionably high. Large amounts of ground water move through the area, producing many brackish basal springs along the shoreline.

Beneath sea level divers have observed what appear to be pillow lavas, and similar lavas are shown in deeper water by photographs (Moore and Fiske, 1969).

Warm ($33^{o}$ C) brackish water issues in the beach at Pohoiki, 7.6 km south-southwest of Cape Kumukahi. Previous to 1960 warm ($29^{o}$ C) brackish basal water was present in a crack on the rift zone 2.4 km west of the cape, and similar water at $32^{o}$ C was present in another crack 1 km to the northwest. The cracks lay close to the borders of the graben that sank in 1924. Both were buried by lava in 1960. A well 6 km west of Cape Kumukahi contained brackish water at $34^{o}$ C. A well 4 km $S80^{o}W$ of Pohoiki contains brackish water at $53^{o}$ C. Many steaming vents are present along the rift zone west of 300 meters altitude, but east of that altitude only minor wisps of steam issue, especially in Pawai Crater, a small pit crater 10 km southwest of Cape Kumukahi. At Pahoa, and 8 km to the south along the Pahoa-Kalapana road, wells produce cold basal water of good quality.

The warm-water wells are distinctly more saline than would be expected (Macdonald, 1973) on the basis of normal Hawaiian basal ground water conditions in other areas of similarly high rainfall and rocks of approximately the same permeability. The well nearly west of Pohoiki had, on completion, a chloride content of 6,500 mg per liter (approximately 6,000 p.p.m.), and the well 6 km west of Cape Kumukahi had a chloride content of 320 p.p.m. Thus there are distinct anomalies in ground water conditions in East Puna, and the most probable cause in heating of the sea water saturating the underlying rocks, probably by hot intrusive masses along the rift zone, decreasing the density of the water to the point where it can no longer support the normal Ghyben-Herzberg lens of fresh water.

Although all of the exposed rocks are moderately to highly permeable, it is possible that less permeable material may exist at depth. Along part of the contact where Kilauea overlaps the slope of Mauna Loa, 35 km west of Cape Kumukahi, Kilauea lavas overlap several feet of relatively impermeable weathered volcanic ash (Stearns and Macdonald, 1946, plate 1). This ash layer lies on the crest of a very broad constructional arch built along an ancient east-trending rift zone of Mauna Loa. Magnetic measurements (Malahoff and Woollard, 1966) suggest that this old rift zone of Mauna Loa continues eastward beneath the cover of Kilauea lavas and merges with the east rift zone of Kilauea approximately at Cape Kumukahi. If so, the ash layer may continue beneath Kilauea lavas to or beyond Cape Kumukahi at some depth below sea level. If it is present, it might conceivably form a tight cap over permeable lavas beneath in such a structural arrangement as to trap or concentrate steam or hot water.

Another possibility for the formation of a zone of less permeable material is related to the presumed history of the submarine growth of the volcano. It is believed that in deep water the eruptions were non-explosive, because of the restraining hydrostatic pressure of the overlying water; but as the volcano grew into shallow water the explosive liberation of magmatic gas became possible, and contact of the erupting magma with water probably caused numerous moderately violent steam explosions like those during the recent eruptions of Surtsey Volcano in Iceland and Capelinhos in the Azores. These would form large amounts of glassy ash that would rapidly become palagonitized. If the ash stayed in place it may constitute an extensive, poorly permeable layer or layers intercalated in the lava flows, possibly forming a relatively tight caprock. Still another possibility is that hyaloclastite, formed in association with pillow lavas and altered to palagonite, may form relatively tight layers in the lava sequence.

Sinking of the island may have carried any of these impermeable layers to considerable depths below the level at which they formed. Thus there is a possibility of stratigraphic and structural traps for several hundreds of meters below sea level.

## Southwest Rift Zone of Kilauea

The second principal rift zone of Kilauea Volcano extends from the caldera southwestward to the coast, and beyond. Little is known about it below sea level. Above sea level it is dotted with about 30 spatter and cinder cones at the vents of prehistoric eruptions. During historic time eruptions occurred along it in 1823, 1868, 1919-1920, and 1971. Vents of the latter eruption, along the upper (northeast) part of the rift zone, are still steaming.

The rift zone is as much as 4 km wide, and near the caldera is bordered by inward-facing fault scarps. Farther southwest the graben structure is less clear, though locally the rift zone is bordered on the northwest by southeast-facing fault scarps. The rift zone lies parallel to, and about 2 to 5 km southeast of, the Kaoiki fault zone, along which the lower slope of Mauna Loa has moved relatively downward in relation to the upper part of the mountain.

The constructional ridge along the southwest rift zone is asymmetrical. Northwestward the Kilauea lavas abut against the slope of Mauna Loa, usually within 2 km of the rift zone. Dips between the rift zone and the Mauna Loa contact are generally about 2 to $3^{\circ}$ southwestward, nearly parallel to the rift zone. Southeast of the rift zone dips range from 4 to $6^{\circ}$ southeastward. The lava flows are pahoehoe and aa, similar to those of East Puna. The rift zone is marked by innumerable open cracks. One of these, the Great Crack, is uninterrupted for almost 25 km along the lower part of the rift zone, and served as the near-surface conduit for the 1823 lava flow.

Warm water has long been known in a crack in Waiwelawela ("Hot Water") Point, at the coast 4 km southeast of the Great Crack. It is brackish, but neither its salinity nor its temperature have been measured. Anomalous ground water conditions exist in the area west of the Great Crack, around Pahala and between there and the ocean. Fresh ground water, apparently part of the basal zone of saturation, stands about 70 meters above sea level in the Pahala well. Whether this high level of ground water is in any way related to the southwest rift zone of Kilauea is unknown. It could result from obstruction of seaward movement of the ground water by faults of the Kaoiki system and/or numerous relatively impermeable dikes in the rift zone, possibly combined with unexposed poorly permeable tephra and/or hyaloclastite below present sea level. The Pahala ash, which is largely palagonitized, reaches thicknesses of as much as 17 meters near Pahala, and is presumably down-dropped along the Kaoiki fault system and buried by later lavas farther seaward.

Southwest Rift Zone of Mauna Loa

One of the two principal rift zones of Mauna Loa extends southwestward from the summit caldera to an altitude of about 2,300 meters, then broadens and turns southward to Ka Lae (South Point). Above 2,300 meters altitude the rift zone is approximately 3 km wide, and is studded with many spatter-and-cinder cones, spatter ramparts, and open fissures. Just south of the caldera are three pit craters. Below 2,300 meters the rift zone broadens to about 6 km, but at about 1,100 meters the western part of the zone dies out and the eastern part continues southward. This southward extension is only about 2 km wide. Along its western edge, the north-trending Kahuku fault has formed a westward-facing scarp 180 meters high near the coast, gradually decreasing in height inland and disappearing near the highway at 600 meters altitude. Between 760 and 975 meters altitude, the Pali o ka Eo is probably a buried west-facing scarp en echelon with, and slightly east of, the Kahuku fault. The rift-zone ridge and the Kahuku fault scarp can be traced southward on the ocean floor for about 35 km behond South Point.

A pit crater lies near the eastern edge of the rift zone at 1,370 m altitude, and three other small ones lie close to the top of the Kahuku fault scarp between 530 and 565 m altitude. These pit craters are partly buried by Pahala Ash, showing that the rift zone has been active at least since the latter part of the eruption of the Kahuku Volcanic Series (Stearns and Macdonald, 1946).

Most of the lavas along the southwest rift zone of Mauna Loa belong to the Kau Volcanic Series (Stearns and Macdonald, 1946). They are tholeiitic basalts of both pahoehoe and aa type, similar to those of Kilauea. East of the rift zone and along the top of the Kahuku fault scarp the Kau lavas rest on Pahala Ash, which in this region ranges from about 2 to 8 m in thickness. The ash is largely palagonitized. Beneath the ash, in Kahuku scarp 180 m of thin-bedded tholeiitic pahoehoe and aa lava flows of the Kahuku Volcanic Series are exposed. No ash beds are intercalated with the lavas below the Pahala Ash.

Since 1832, seven eruptions have taken place along the southwest rift zone. Most were from vents above 2,300 meters altitude, but in 1868 an eruption took place from fissures near the eastern edge of the rift zone between 600 and 1,100 meters altitude. Lava from the fissures flowed into the ocean west of the Kahuku fault scarp, the more easterly of the two major flows lying directly against the base of the scarp. One of the two largest eruptions of Mauna Loa in history took place in 1950, pouring out more than 460,000,000 cubic meters of lava from vents between 2,400 and 3,800 meters altitude on the southwest rift zone (Finch and Macdonald, 1953).

No historic movement is known to have occurred on the Kahuku fault. During a strong (intensity X mM) earthquake in 1868, movement occurred on the Waiohinu fault, 8 km east of the Kahuku fault. It is inferred that other movement occurred at the same time beneath the ocean, because a big local tsunami was generated, but no movement was observed on the Kahuku fault above sea level.

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The geophysical background is reviewed in Section II of the geophysics program in this proposal.

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## SELF POTENTIAL STUDY

Charles J. Zablocki

Studies made by the U.S. Geological Survey in many areas of Kilauea in recent years have indicated that self potential measurements appear to be the single most useful method for identifying anomalous thermal areas. Anomalies have also been found in areas which have no obvious sufrace manifestations. Their locations, however, are in areas which reasonably could contain localized heat sources.

In brief, the large potentials observed at the surface are thought to be related to the flow of hydrothermal fluids in a convection system (electrofiltration phenomenon). Although most of these studies have been made near and at the summit of Kilauea, some measurements made in a few areas of the lower east rift zone (Puna district) have revealed some interesting findings (Figure 1). Not only were large potentials observed over the still-steaming vents of the 1955 eruption ( 3 miles south of Pahoa ), but the asymmetry of the resulting contoured data suggest a north dip to the related intrustion (Figure 2). Measurements made about 4 1/2 miles farther east along the rift zone delineated an anomaly in an area that has no surface indications of near-surface heat source (Figure 3). Only weak anomalies were observed over some of the 1955 eruptive fissures nearby. Curiously, the large anomaly is located in the area where the 1955 rift eruption was offset and coincides with the general epicentral area of recurrent shallow earthquake swarms in recent years.

Because of these results, a cooperative study is presently underway with the U.S. Geological Survey to make a detailed survey of the lower east rift zone of Kilauea in an effort to help locate the sites for the exploratory drilling program.

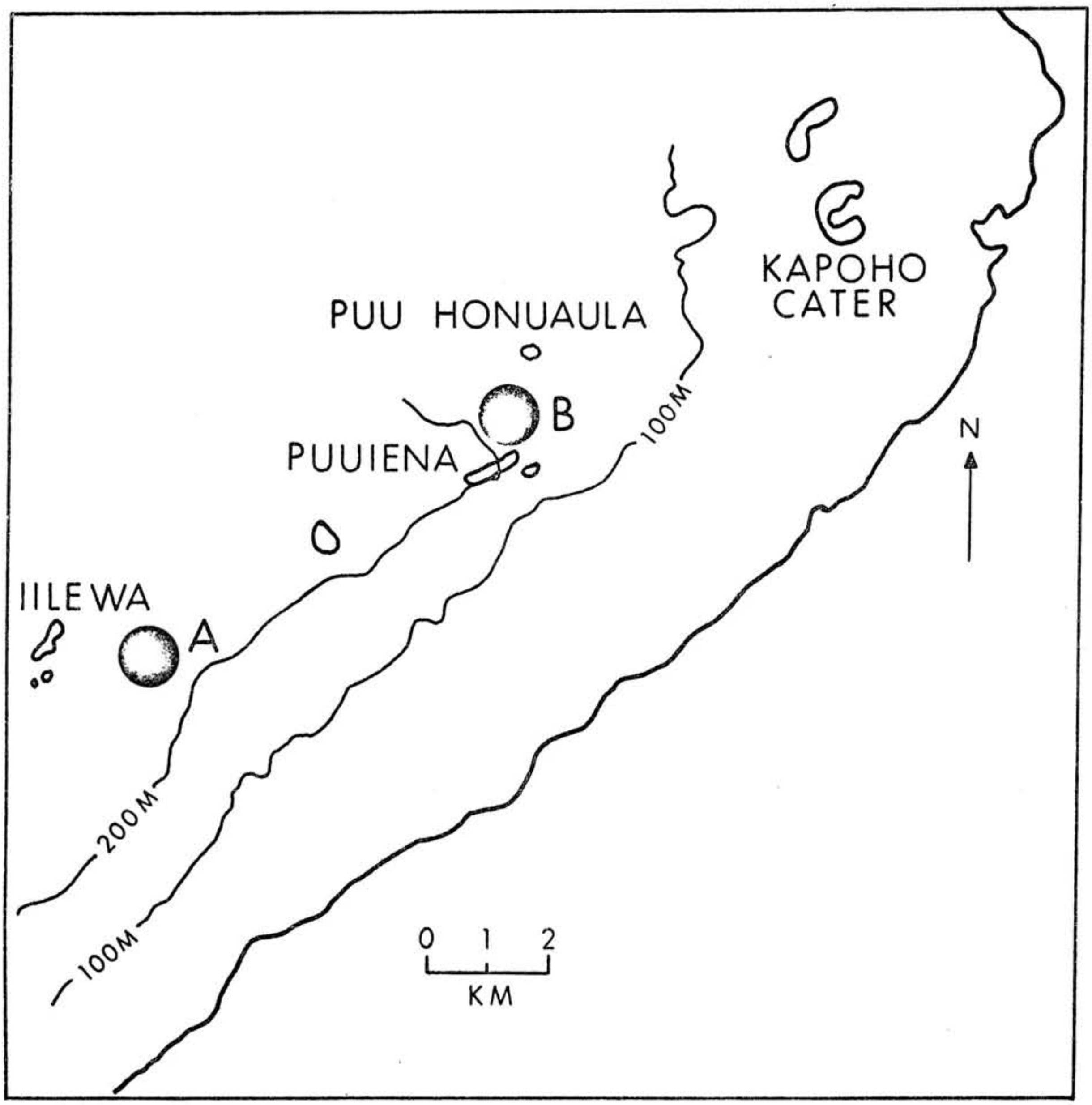


Figure 1

Areas Measured

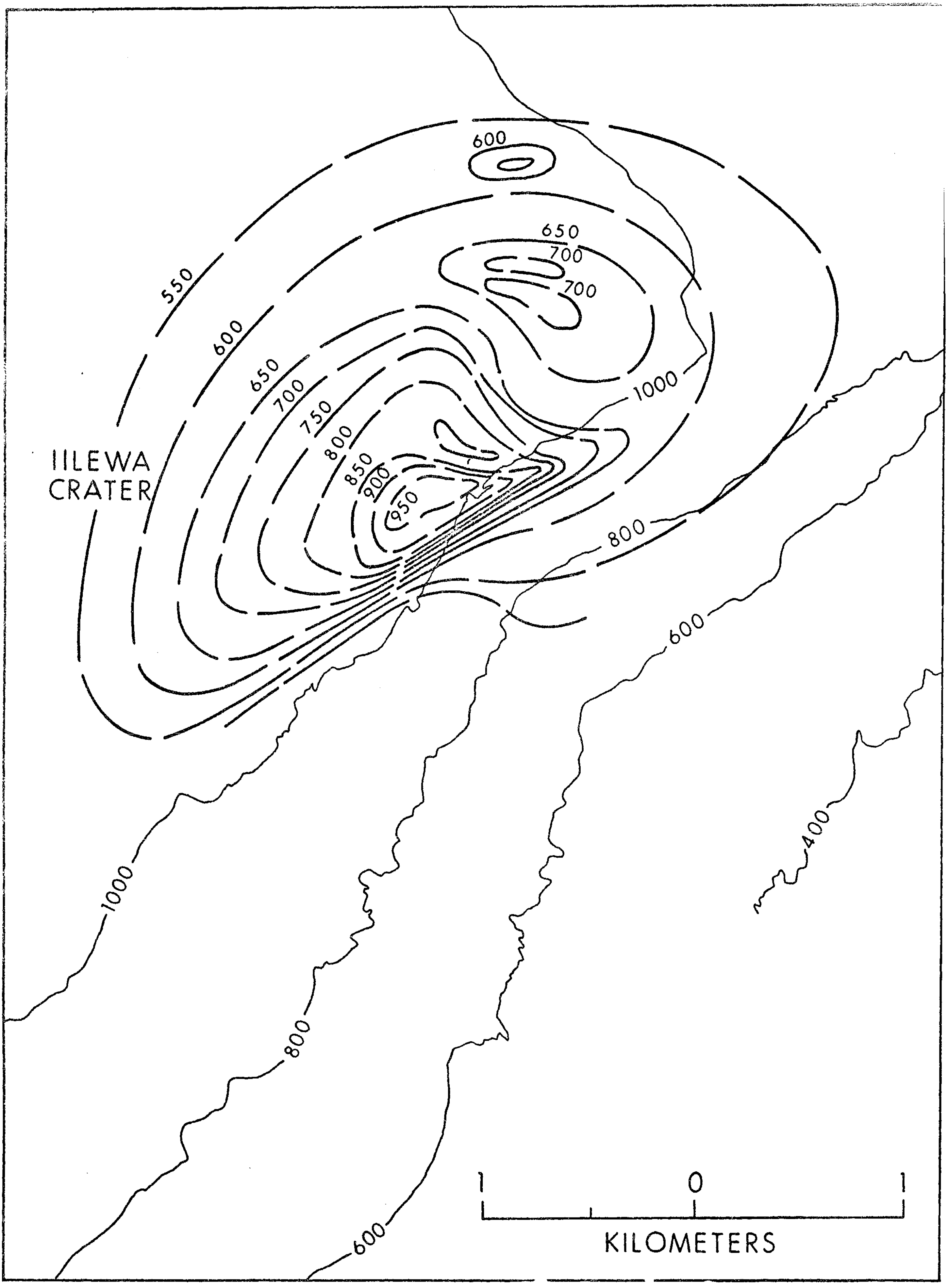


Figure 2 Self Potential Contours

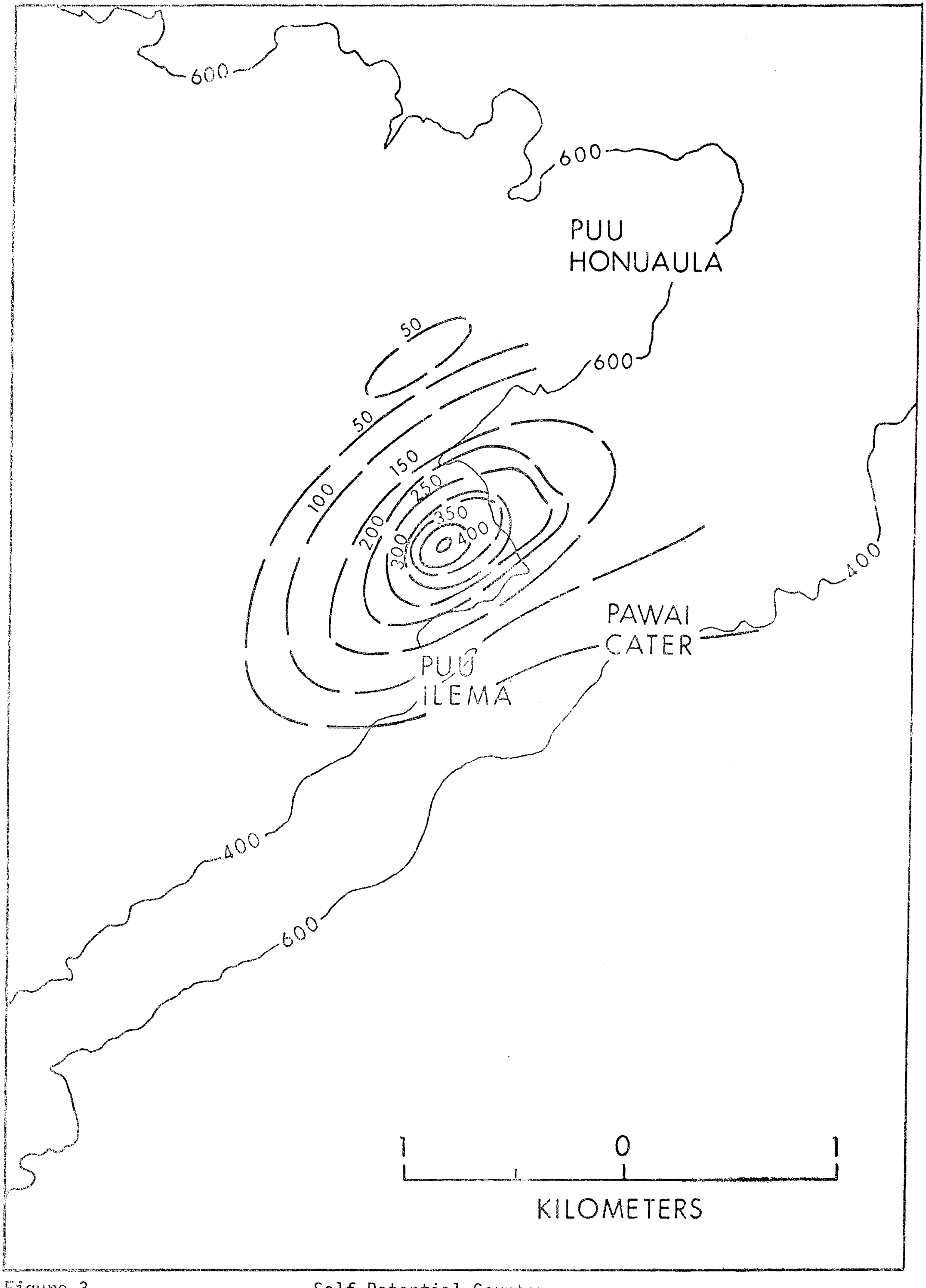


Figure 3 Self Potential Countours